

XVI NExT Ph.D. Workshop – Cosener's House 24-26 August 2026

3 lectures on:

Neutrino Physics and Particle Cosmology

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(<http://www.hep.phys.soton.ac.uk/~pdb1d08/teaching.html>)



Plan

1) Neutrinos

2) Cosmology

3) Neutrino cosmology

Lecture II

Cosmology

- Λ CDM model and cosmological tensions

References

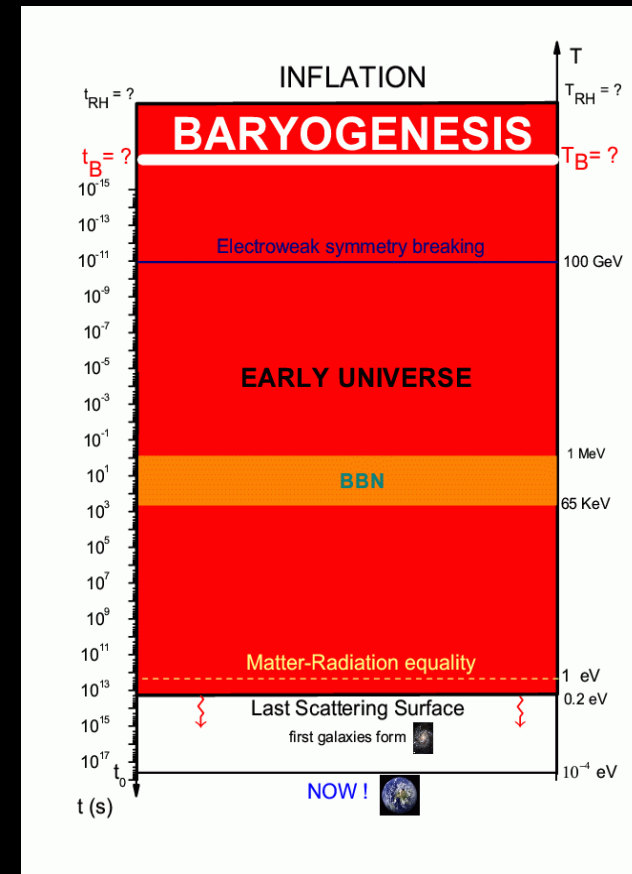
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- H.Davoudiasl and R.Mohapatra, *On Relating the Genesis of Cosmic Baryons and Dark Matter*, arXiv:1203.1247
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Friedmann Cosmology

Geometry of the Universe

Assuming homogeneity and isotropy of space (cosmological principle)

⇒ Friedmann-Robertson-Walker metric (comoving system):

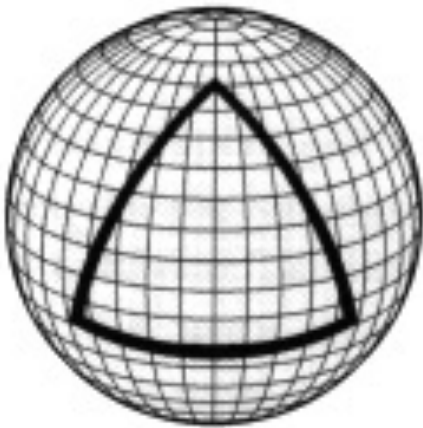
$$ds^2 = c^2 dt^2 - a^2(t) R_0^2 \left(\frac{dr^2}{1 - k r^2} + r^2 d\Omega^2 \right)$$

$a(t) \equiv R(t)/R_0$ is the *scale factor*

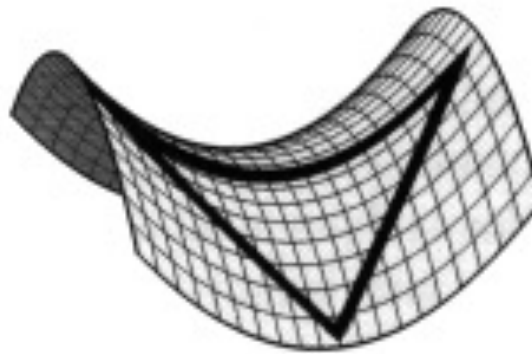
$\kappa=+1$

$\kappa=-1$

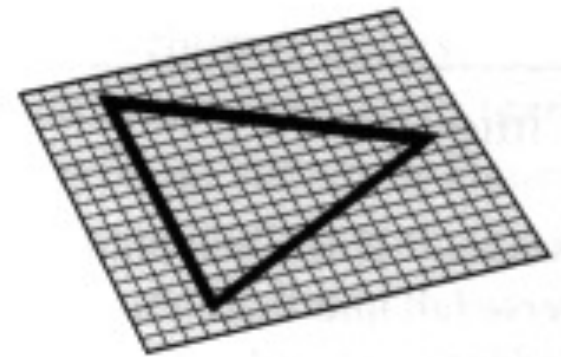
$\kappa=0$



Closed Geometry



Open Geometry



Flat Geometry

Hubble's law from theory

Proper
distance

$$d_{\text{pr}}(t) = a(t) R_0 \int_0^r \frac{dr'}{\sqrt{1 - k r'^2}}$$

$\Rightarrow$

$$\dot{d}_{\text{pr}}(t) = \dot{a}(t) d_{\text{pr}}(t_0)$$

$d_{\text{pr},0}$

Proper
velocity

$$v_{\text{pr}}(t) \equiv \dot{d}_{\text{pr}}(t)$$

Lemaitre
equation

$$v_{\text{pr}}(t) = H(t) d_{\text{pr}}(t)$$

expansion rate

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)} = \frac{d \ln a(t)}{dt}$$

At the present time:

$$v_{\text{pr},0} = H_0 d_{\text{pr},0}$$

Hubble constant

The cosmological expansion

Cosmological principle: homogeneity and isotropy

Redshift of momenta:

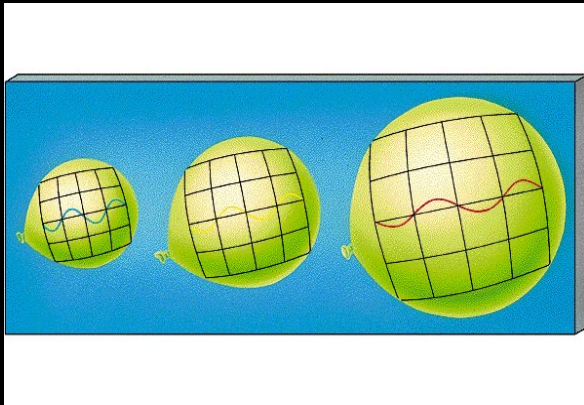
$$|\vec{p}|(t) = |\vec{p}|_{\text{in}} \frac{a_{\text{in}}}{a(t)} \propto a(t)^{-1}$$

In the case of photons:

$$|\vec{p}| = \hbar/\lambda,$$

$\Rightarrow$

$$\lambda(t) = \lambda_0 \frac{R(t)}{R_0} = a(t) \lambda_0.$$



The wavelength is stretched by the expansion!

cosmological redshift:

$$z \equiv \frac{\lambda_0}{\lambda_{\text{em}}} - 1 = \frac{R_0}{R_{\text{em}}} - 1 = a_{\text{em}}^{-1} - 1,$$

At the present time one can relate the proper distance to the luminosity distance and redshift:

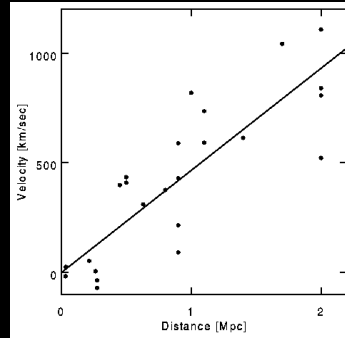
$$d_L(z) = (1 + z) d_{\text{pr},0}(z) = c H_0^{-1} \left[z + z^2 \left(\frac{1 - q_0}{2} \right) \right] + \mathcal{O}(z^3).$$

Hubble's law

$$d_L(z) = c H_0^{-1} z + \mathcal{O}(z^2)$$

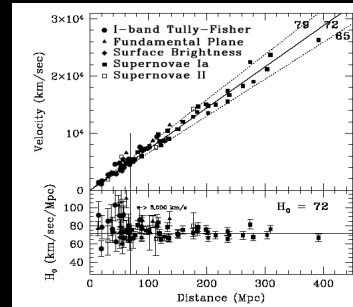
Hubble constant measurements

Edwin
Hubble
(1929)



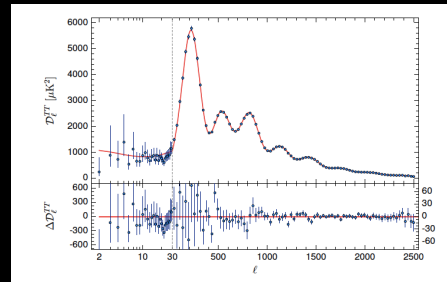
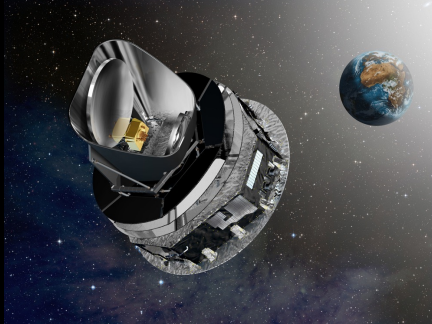
$$H_0 \sim 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Hubble
Space
Telescope
Key Project
(2001)



$$H_0 = (72 \pm 8) \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Planck
2018
+ Λ CDM



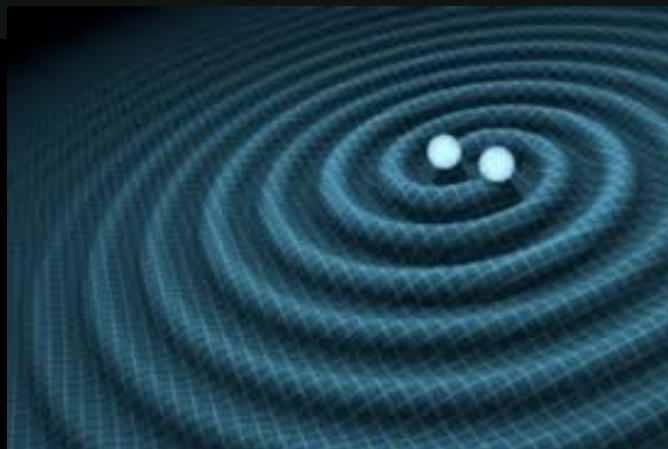
$$H_0 = 67.66 \pm 0.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

5 σ tension
("Hubble tension")

Hubble
Space
Telescope,
Riess et al.
(2021)

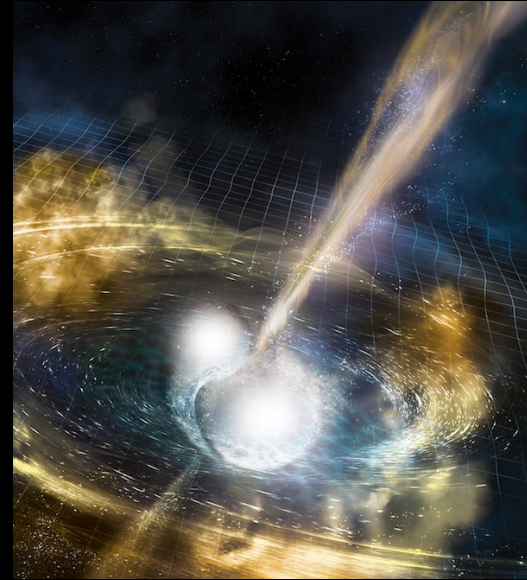


$$H_0 = 73.30 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$$



GW170817: The first observation of gravitational waves from a binary neutron star inspiral

(almost) coincident
detection of GW's and light:
one can measure distance
from GW's "sound" and
redshift from light:
STANDARD SIREN!



A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION,
THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION,
THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION,
THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.

[arXiv:1710.05835](https://arxiv.org/abs/1710.05835)

$$H_0 = 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

~50 more detections of standard sirens should reduce the error
below and solve the current tension between Planck and HST measurements

Fundamental equations of Friedmann cosmology

Einstein
equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$\Rightarrow$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3} \varepsilon - \frac{k}{a^2 R_0^2}$$

Friedmann
equation

Energy-momentum
tensor conservation

$$T^{\mu\nu}_{;\nu} = 0$$

$\Rightarrow$

$$\frac{d(\varepsilon a^3)}{dt} = -p \frac{da^3}{dt}$$

Fluid
equation

Friedmann equation
+ Fluid equation

$\Rightarrow$

$$\ddot{a} = -4\pi G(\varepsilon + 3p)a$$

acceleration
equation

Critical energy
density

$$\varepsilon_c \equiv \frac{3H^2}{8\pi G}$$

energy density
parameter

$$\Omega \equiv \frac{\varepsilon}{\varepsilon_c} = \sum_i \Omega_{X_i}$$

$$k \equiv H_0^2 R_0^2 (\Omega_0 - 1) \Rightarrow$$

$\Omega_0 < 1 \Leftrightarrow k = -1$ open Universe

$\Omega_0 = 1 \Leftrightarrow k = 0$ flat Universe

$\Omega_0 > 1 \Leftrightarrow k = +1$ closed Universe

For dynamical models the Friedmann equation can be re-expressed as:

$$\dot{a}^2 = H_0^2 \Omega_0 a^2(t) \frac{\varepsilon(t)}{\varepsilon_0} + H_0^2 (1 - \Omega_0)$$

Is there a Newtonian analogy ? Not really!

Apparently the Friedmann equation looks like an energy conservation equation. If one has a solution $\varepsilon=\varepsilon(a)$ then one can write it in the form:

$$\frac{\dot{a}^2}{H_0^2} + V(a) = E_0, \text{ where } E_0 \equiv 1 - \Omega_0 \text{ and } V(a) \equiv -\frac{8\pi G}{3H_0^2} \varepsilon(a) a^2 = -a^2 \Omega_0 \frac{\varepsilon(a)}{\varepsilon_0}$$

....but on the other hand the energy-momentum conservation equation tells that the gas is making work during the expansion losing energy

$$\frac{d(\varepsilon a^3)}{dt} = -p \frac{da^3}{dt}$$

For a perfect gas this equation is equivalent to the redshift of the momenta

Therefore the Friedmann Equation, even though has the form of a conservative uni-dimensional system, does not have a Newtonian analogy: the scale factor expansion is a general relativistic effecthowever the observation that there is a prime integral of the motion is useful, as we will see in a moment...

Building a cosmological model: general strategy

- Assume an equation of state: $p=p(\varepsilon)$
- Plug the equation of state into the fluid equation

$$\frac{d(\varepsilon a^3)}{dt} = -p \frac{da^3}{dt} \Rightarrow \varepsilon = \varepsilon(a)$$

- Finally plug $\varepsilon(a)$ into the Friedmann equation

$$\dot{a}^2 = H_0^2 \Omega_0 a^2(t) \frac{\varepsilon(t)}{\varepsilon_0} + H_0^2 (1 - \Omega_0) \Rightarrow a=a(t) \Rightarrow \varepsilon = \varepsilon(t)$$

- Example: matter universe

$$p_M=0 \Rightarrow \varepsilon_M = \varepsilon_{M0}/a^3 \Rightarrow (\text{flat universe}) a(t) = (t/t_0)^{2/3}, t_0 = 2H_0^{-1}/3$$

The age of the Universe

It is unambiguously defined for models with an initial singularity as the interval of time elapsed from the singularity: $a(t=0)=0$

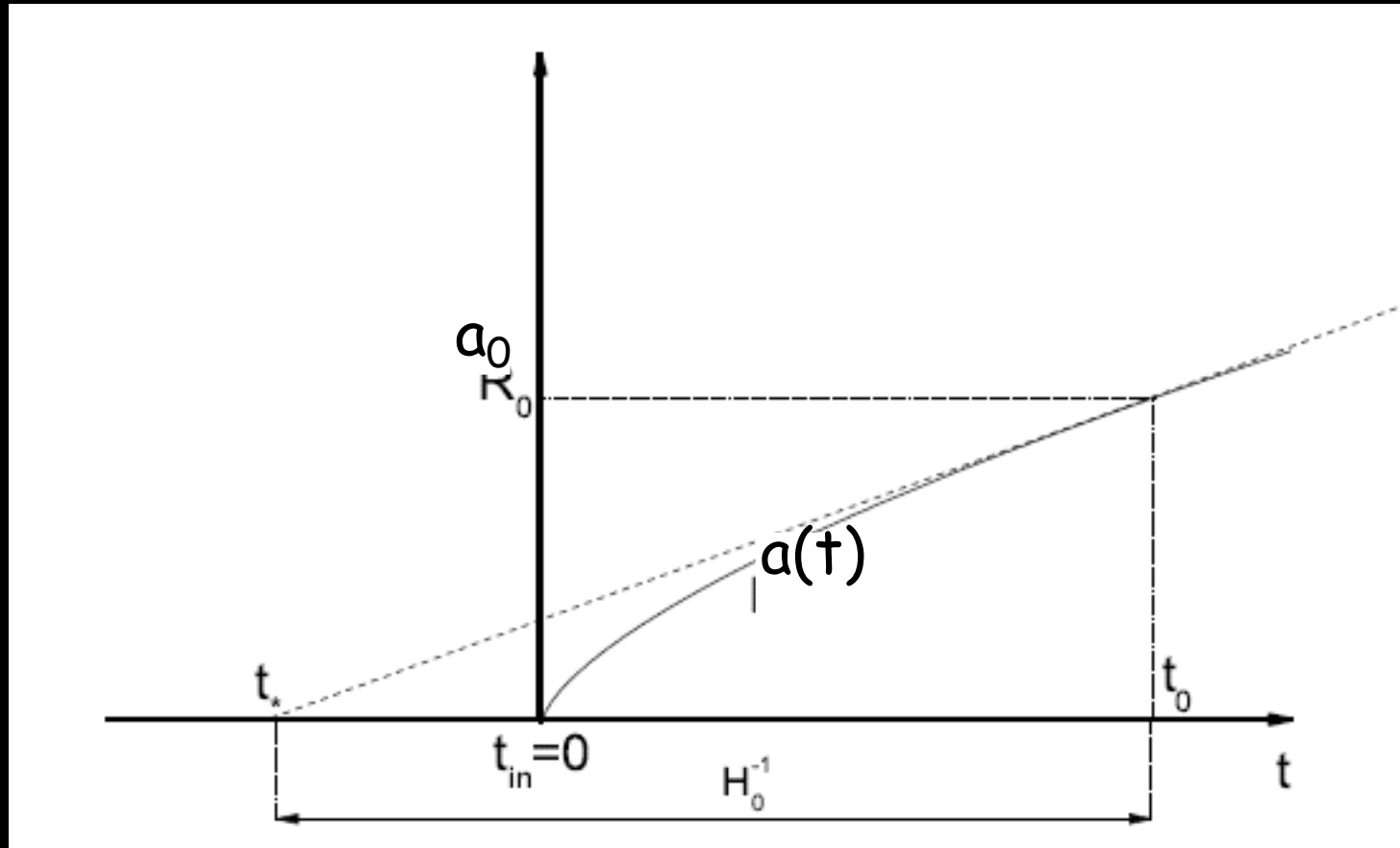
General expression for the age of the Universe (at present):

$$t_0 = H_0^{-1} f_\varepsilon(\Omega_0), \quad f_\varepsilon(\Omega_0) \equiv \int_0^1 \frac{da}{\sqrt{\Omega_0 a^2 \frac{\varepsilon(a)}{\varepsilon_0} + (1 - \Omega_0)}},$$

From this general expression one can see that there are two solutions compatible with the age of the globular clusters (~ 14 Gyr):

- An open Universe with $\Omega_0 \simeq 0.2$ and no cosmological constant
- A flat Universe with a cosmological constant ($\Omega_{\Lambda,0} \simeq 0.7$)

Graphical representation of the age of the Universe (example of a ever-decelerating expansion)



$$a_0 = \dot{a}_0 (t_0 - t_*) \Rightarrow H_0^{-1} = (a_0 / \dot{a}_0) = t_0 - t_*$$

Models with one fluid and $p/\varepsilon = \omega = \text{const}$

$$\frac{d(\varepsilon a^3)}{dt} = -p \frac{da^3}{dt} \quad \Rightarrow \quad \varepsilon a^{3(1+\omega)} = \text{const}$$

3 cases:

$$\omega > -\frac{1}{3} \Rightarrow \ddot{a} < 0, t_0 < H_0^{-1}$$

$$\omega = -\frac{1}{3} \Rightarrow \ddot{a} = 0, t_0 = H_0^{-1}$$

$$\omega < -\frac{1}{3} \Rightarrow \ddot{a} > 0, t_0 > H_0^{-1}$$

Flat Universe with 1 fluid : summary of results

	equation of state	fluid equation ↓	Friedmann equation ↓ (flat Universe)	Age of the Universe (flat universe)	energy density vs. time (flat universe)
matter universe	$p_M = 0$	$\varepsilon_M(a) = \frac{\varepsilon_{M,0}}{a^3} \propto a^{-3}$	$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{3}}$	$t_0 = \frac{2}{3} H_0^{-1} = (9.40 \pm 0.15) \text{ Gyr}$	$\varepsilon_M(t) = \varepsilon_0 \left(\frac{t_0}{t}\right)^2$
radiation universe	$p_R = \frac{1}{3} \varepsilon_R$	$\varepsilon_R = \frac{\varepsilon_{R,0}}{a^4} \propto a^{-4}$	$a(t) = \left(\frac{t}{t_0}\right)^{1/2}$	$t_0 = \frac{1}{2} H_0^{-1} = (7.05 \pm 0.12) \text{ Gyr}$	$\varepsilon_R(t) = \varepsilon_0 \left(\frac{t_0}{t}\right)^2$
	if	$\varepsilon_R \propto T_R^4 \Rightarrow T_R \propto a^{-1}$			
fluids with constant p/ε	$p = \omega \varepsilon$ $(\omega \neq -1)$	$\varepsilon(a) = \frac{\varepsilon_0}{a^{3(1+\omega)}}$	$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+\omega)}}$ $\omega > -1$	$t_0 = \frac{2}{3(1+\omega)} H_0^{-1}$	$\varepsilon(t) = \varepsilon_0 \left(\frac{t_0}{t}\right)^2$
de Sitter model	$p = -\varepsilon$ $\omega = -1$	$\varepsilon = \varepsilon_0 = \text{const}$	$a(t) = e^{H_0(t-t_0)}$	INFINITE !	$\varepsilon = \varepsilon_0 = \text{const}$

Multi-fluid models

Consider an admixture of different fluids:

$$\varepsilon = \sum_i \varepsilon_i, \quad p = \sum_i p_i \Rightarrow \Omega = \sum_i \Omega_i \quad \text{with} \quad \Omega_i \equiv \frac{\varepsilon_i}{\varepsilon_c}$$

if each fluid has an equation of state $p_i = p_i(\varepsilon_i)$ and assuming that there is no exchange of energy among fluids (e.g., decaying matter) then the fluid equation decomposes in a fluid equation for each fluid with solutions

$$\varepsilon_i = \varepsilon_i(a) \Rightarrow \varepsilon(a) = \sum_i \varepsilon_i(a)$$

Special case case: $p_i = \omega_i \varepsilon_i$ with $\omega_i = \text{const}$

$$\Rightarrow \varepsilon(a) = \sum_i \frac{\varepsilon_{i0}}{a^{3(1+\omega_i)}}$$

Matter-radiation model

Consider an admixture of 2 fluids: **matter** (M) and **radiation** (R) :

$$p = p_M + p_R, \quad \varepsilon = \varepsilon_M + \varepsilon_R$$

with equations of state:

$$p_M = 0, \quad p_R = \frac{1}{3} \varepsilon_R,$$

That, from the fluid equation, lead to :

$$\varepsilon_M = \frac{\varepsilon_{M,0}}{a^3}, \quad \varepsilon_R = \frac{\varepsilon_{R,0}}{a^4}$$

The **equality matter-radiation time** is defined as:

$$\frac{\varepsilon_{M0}}{a_{eq}^3} = \frac{\varepsilon_{R0}}{a_{eq}^4} \Rightarrow a_{eq} = \frac{\varepsilon_{R0}}{\varepsilon_{M0}} = \frac{\Omega_{R0}}{\Omega_{M0}}$$

Friedmann cosmology as a conservative system

In terms of H_0 and Ω_0 the Friedmann equation can be recast as:

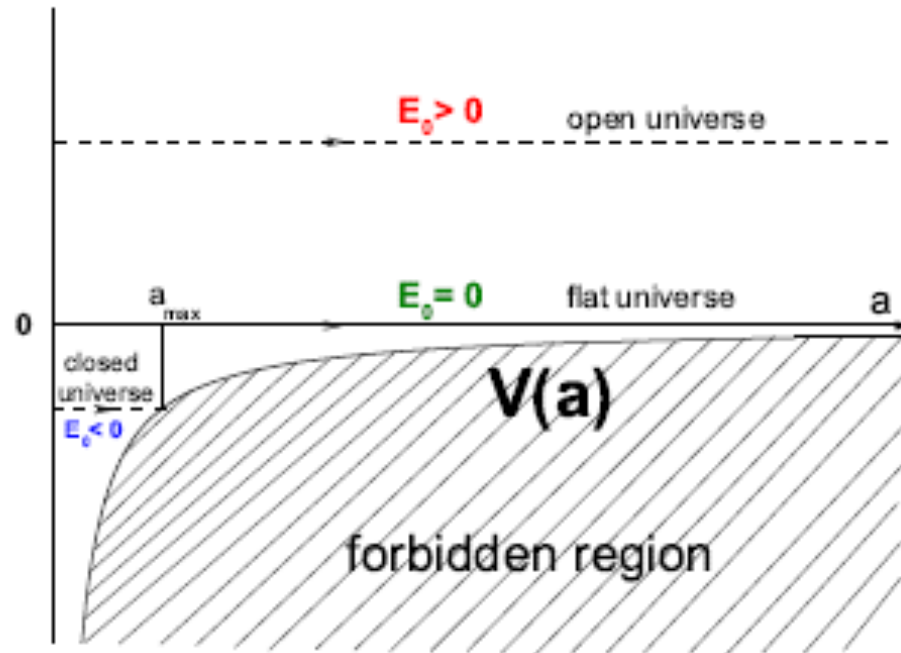
$$\frac{\dot{a}^2}{H_0^2} = \Omega_0 \frac{\varepsilon a^2}{\varepsilon_0} + (1 - \Omega_0)$$

If $\varepsilon = \varepsilon(a)$ then we can define:

$$V(a) = -\Omega_0 \frac{\varepsilon(a) a^2}{\varepsilon_0}, \quad E_0 \equiv 1 - \Omega_0 \Rightarrow \frac{\dot{a}^2}{H_0^2} + V(a) \equiv E(a) = E_0$$

Showing that the Friedmann equation has an integral of motion, $E(a)$, and is, therefore, a conservative system: this will be useful to find the set of solutions for specific models

Matter-Radiation Universe: effective potential analysis



Lemaitre models

Admixture of 3 fluids: matter (M) + radiation (R) + Λ -like fluid (Λ) :

$$p = p_M + p_R + p_\Lambda, \quad \varepsilon = \varepsilon_M + \varepsilon_R + \varepsilon_\Lambda$$

with equations of state:

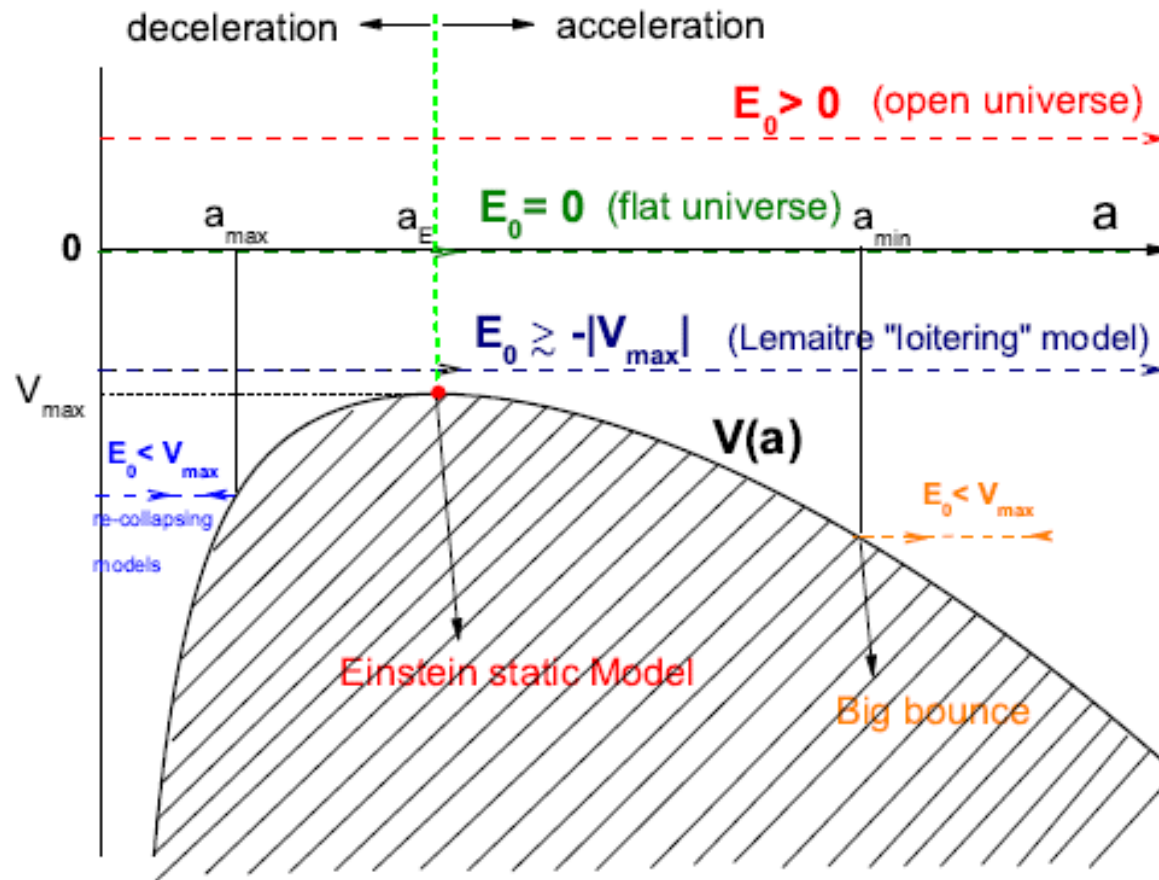
$$p_M = 0, \quad p_R = \frac{1}{3} \varepsilon_R, \quad p_\Lambda = -\varepsilon_\Lambda$$

That, from the fluid equation, lead to :

$$\varepsilon_M = \frac{\varepsilon_{M,0}}{a^3}, \quad \varepsilon_R = \frac{\varepsilon_{R,0}}{a^4}, \quad \varepsilon_\Lambda = \varepsilon_{\Lambda,0}$$

$$\Rightarrow V(a) = -a^2 \left(\frac{\Omega_{R,0}}{a^4} + \frac{\Omega_{M,0}}{a^3} + \Omega_{\Lambda,0} \right)$$

Lemaitre models: effective potential analysis



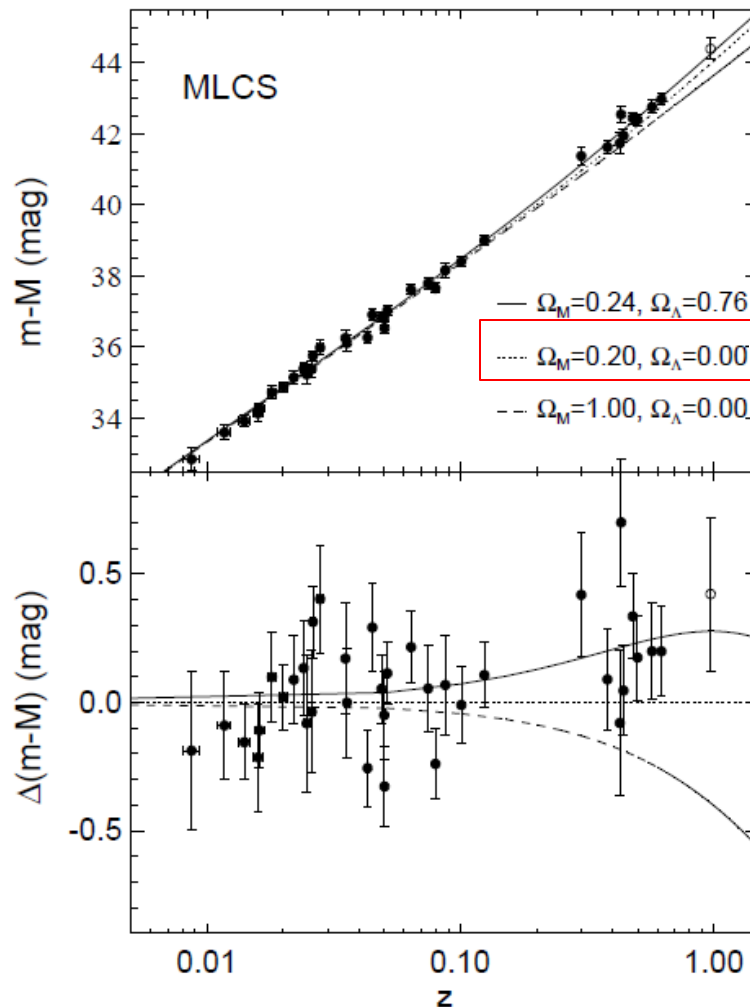
Cosmological observations and the Λ CDM model

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

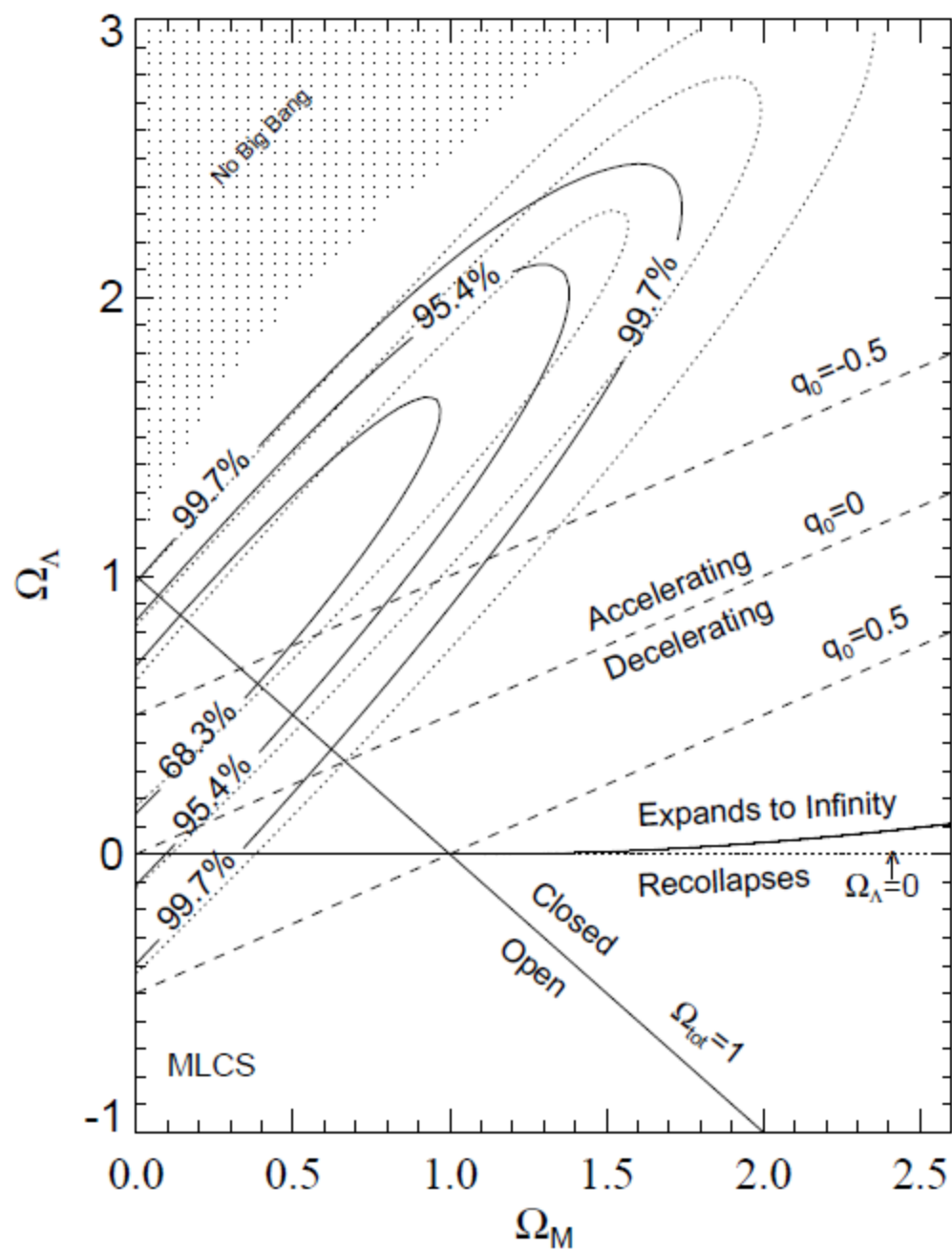
ADAM G. RIESS,¹ ALEXEI V. FILIPPENKO,¹ PETER CHALLIS,² ALEJANDRO CLOCCHIATTI,³ ALAN DIERCKS,⁴
 PETER M. GARNAVICH,² RON L. GILLILAND,⁵ CRAIG J. HOGAN,⁴ SAURABH JHA,² ROBERT P. KIRSHNER,²
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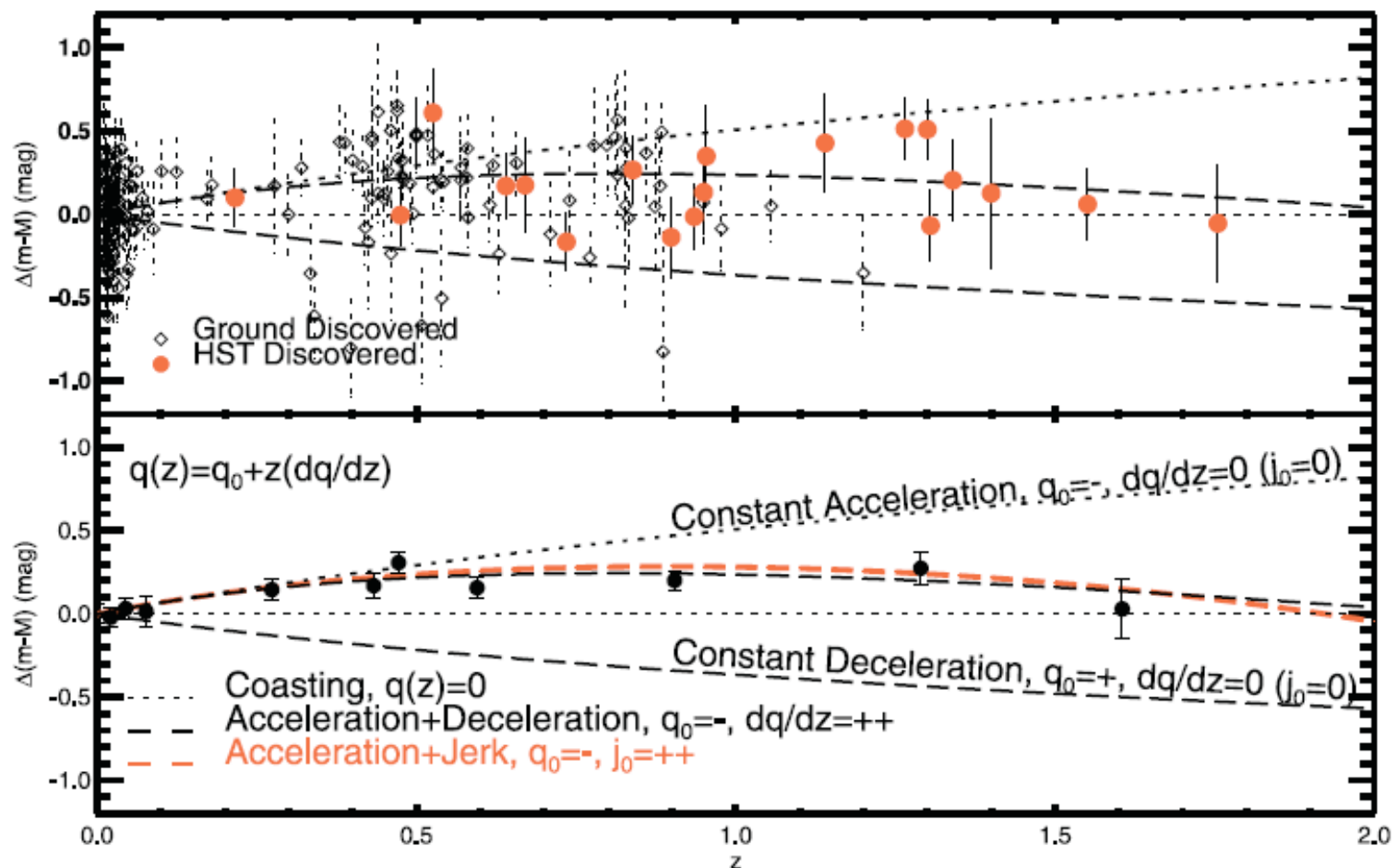
Received 1998 March 13; revised 1998 May 6

$$m - M = 5 \log \left(\frac{d_L}{1 \text{ Mpc}} \right) + 25$$



Differences with respect to
 The values predicted by the
 open model

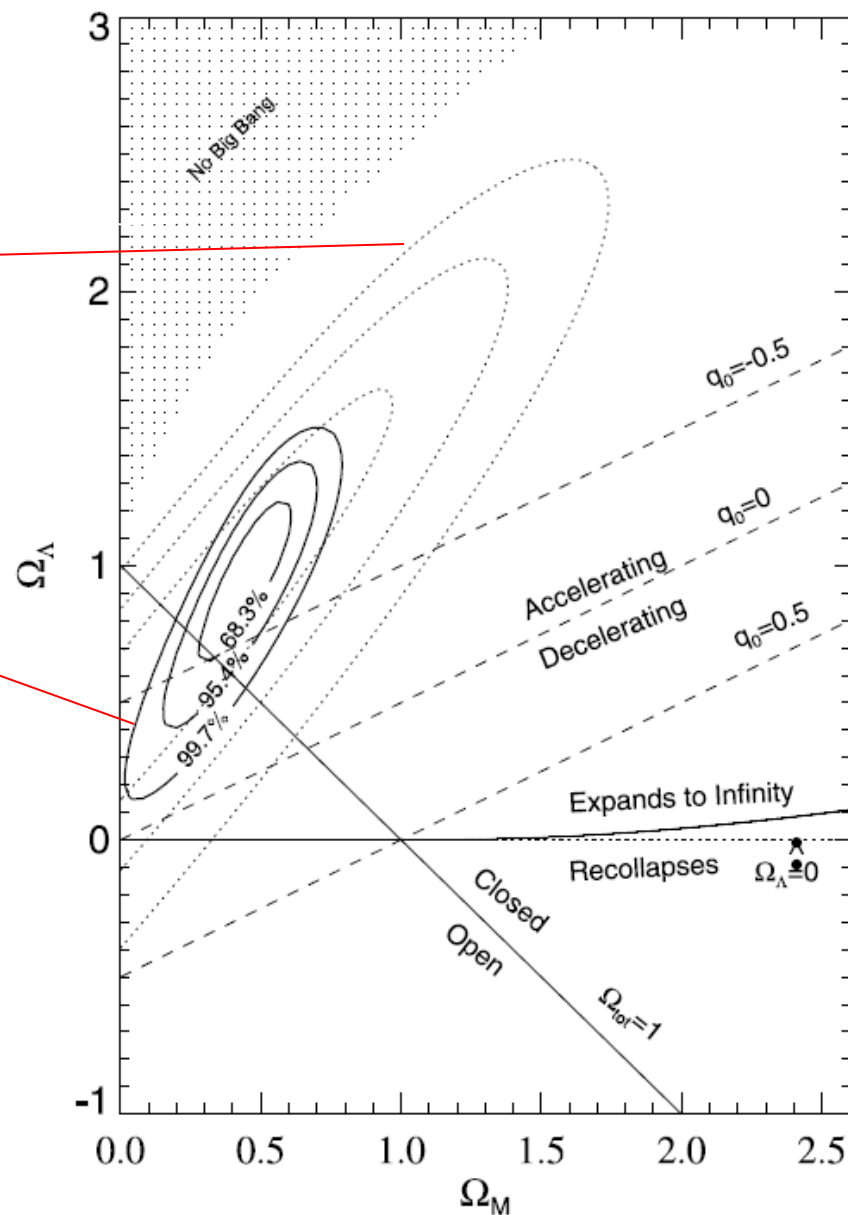




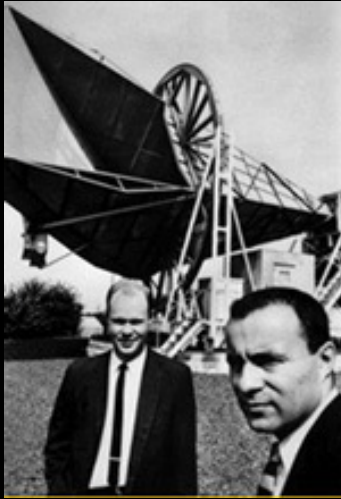
A. G. Riess *et al.* [Supernova Search Team Collaboration], *Type Ia Supernova Discoveries at $z \lesssim 1$ From the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution*, *Astrophys. J.* **607** (2004) 665.

Old results

New results



The discovery of the cosmic microwave background radiation



Penzias and Wilson (1965)

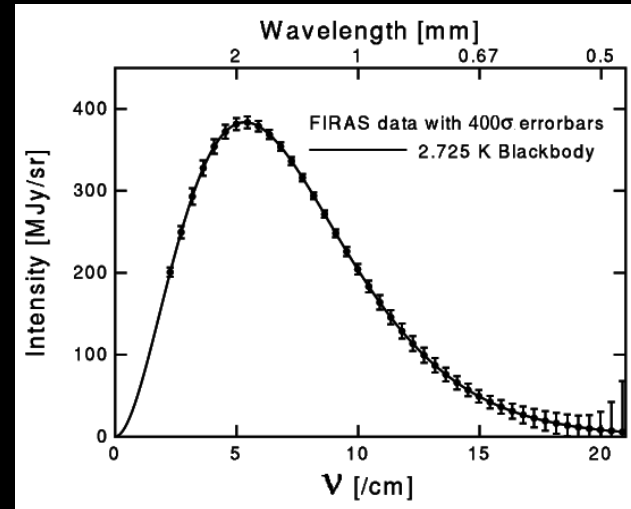
$$T_{\gamma 0} = (3.5 \pm 1) \text{ }^{\circ}\text{K}$$



COBE satellite

FIRAS instrument of COBE (1990)

$$T_{\gamma 0} = (2.725 \pm 0.002) \text{ }^{\circ}\text{K} \Rightarrow n_{\gamma 0} \simeq 411 \text{ cm}^{-3}$$

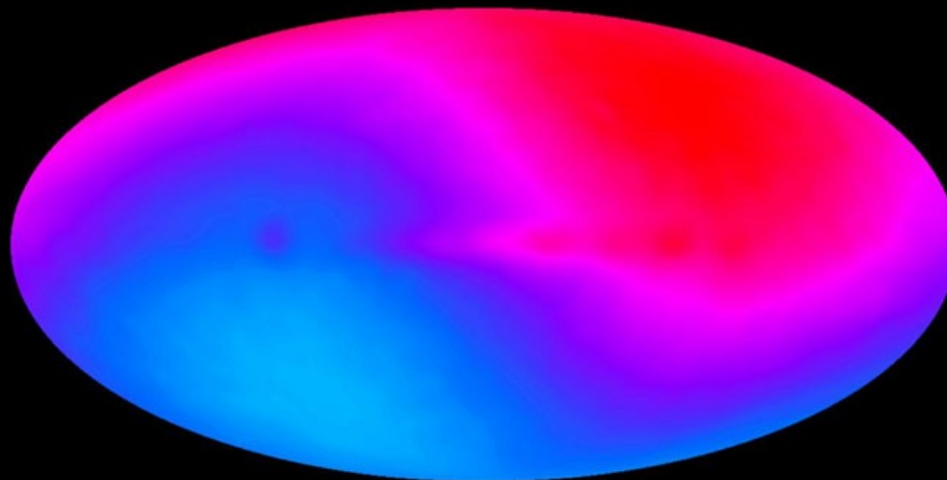


$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

$$\Delta\theta = \frac{180^\circ}{\ell}$$

Example: the dipole anisotropy ($\Delta\theta=180^\circ$) corresponds to $\ell=1$

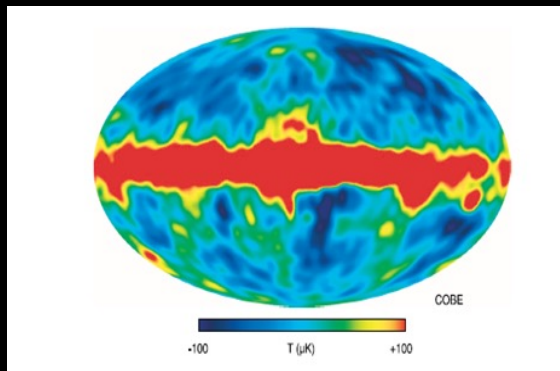
COBE DMR microwave map of the sky in Galactic coordinates:
 temperature variation with respect to the mean value $\langle T \rangle = 2.725$ K. The
 color change indicates a fluctuation of $\Delta T \sim 3.5$ mK $\Rightarrow \Delta T/T \sim 10^{-3}$



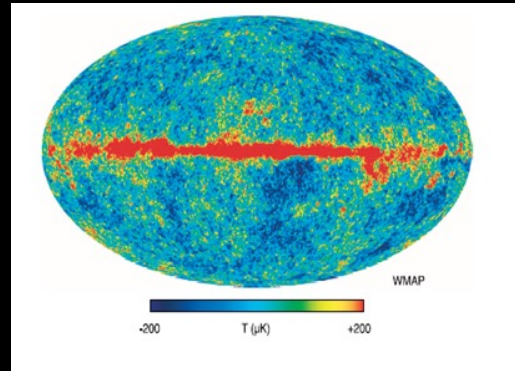
CMB temperature anisotropies

After subtraction of the dipole anisotropy, higher multipole anisotropies are measured with a much lower amplitude than the dipole anisotropy $\Rightarrow T/T \sim 10^{-5}$

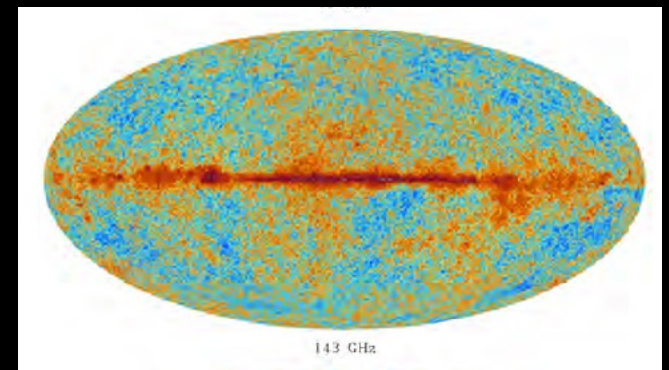
COBE (1992)



WMAP (2003)



Planck
(2013)



The angular resolution of COBE was about $\delta\theta^{\text{COBE}} \simeq 7^\circ$, that one of WMAP is $\delta\theta^{\text{WMAP}} \simeq 10'$, while that one of Planck is $\delta\theta^{\text{Planck}} \simeq 3'$

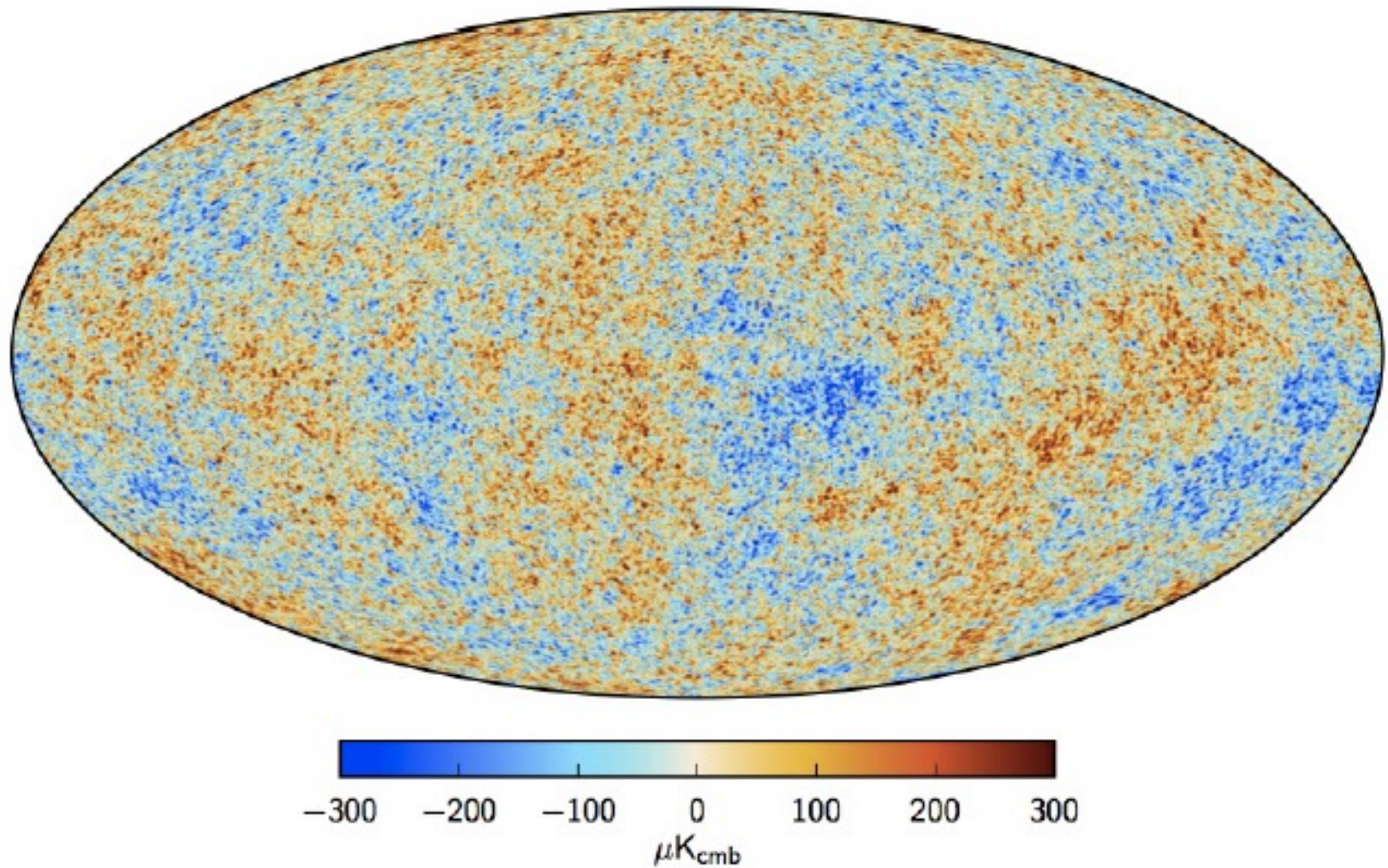
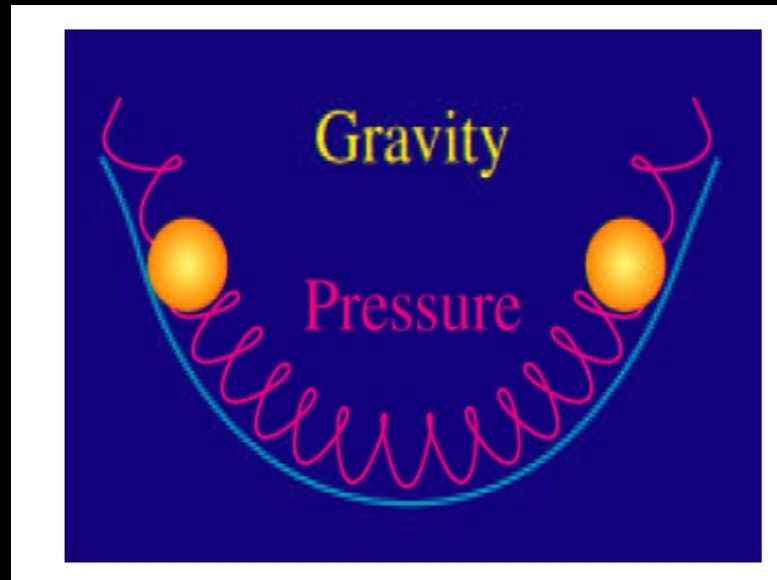


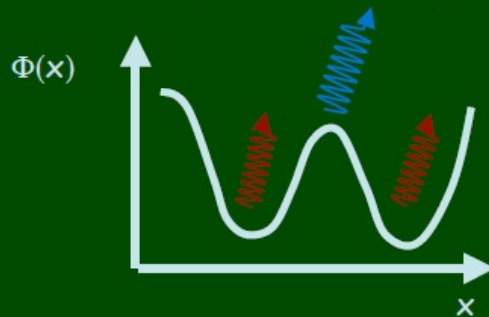
Fig. 9. Maximum posterior CMB intensity map at $5'$ resolution derived from the joint baseline analysis of *Planck*, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6 % of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky.

Acoustic oscillations

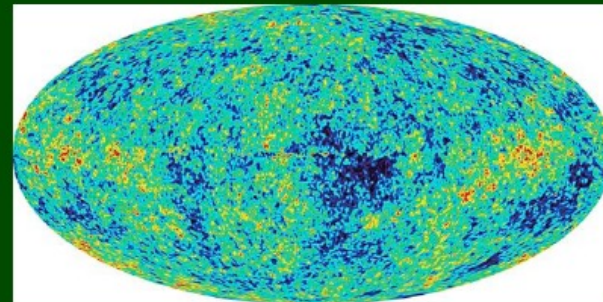


- o Photons escape from gravitational potential

Cold spots = high density
Hot spots = low density



- o ...Translate into fluctuations in the blackbody photon temp at $\sim 1/100,000$ level



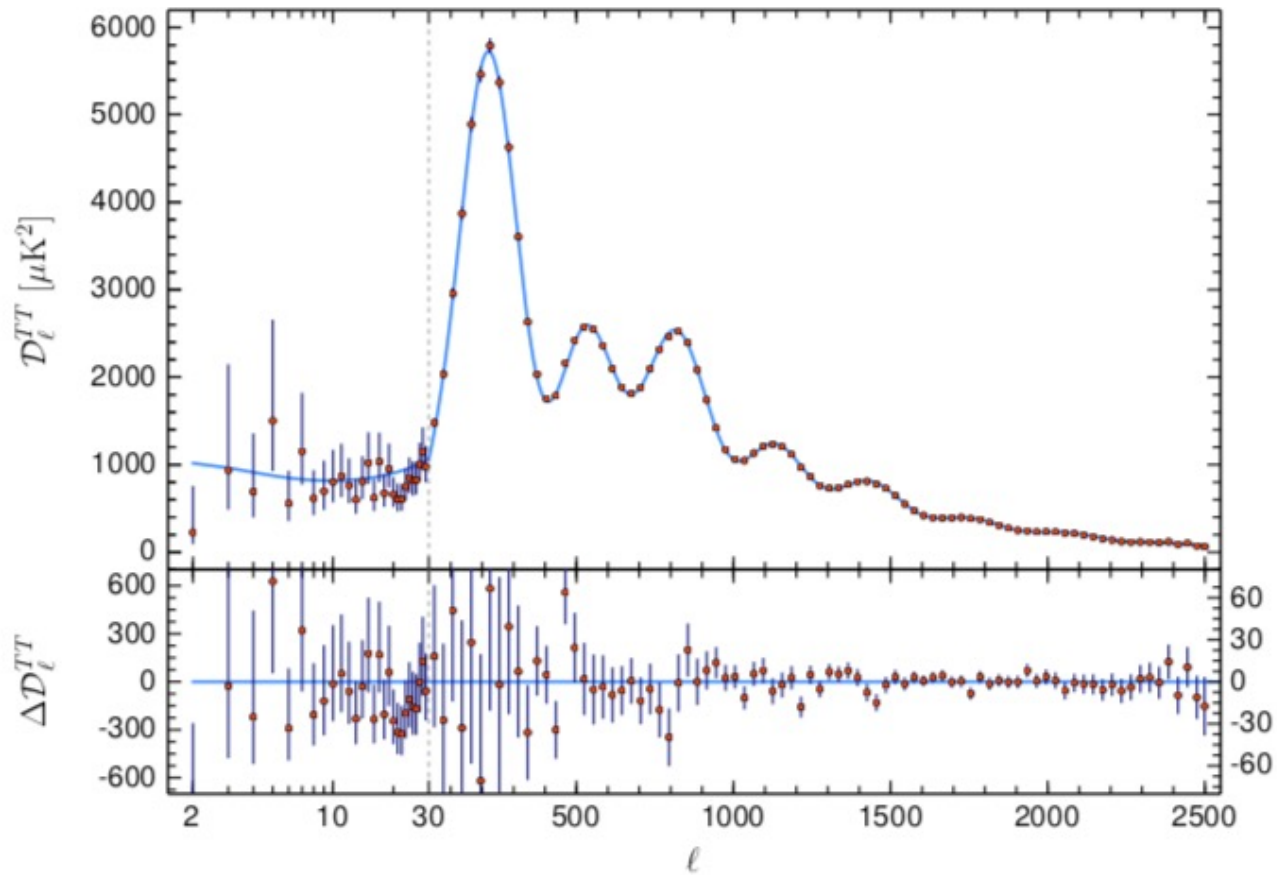


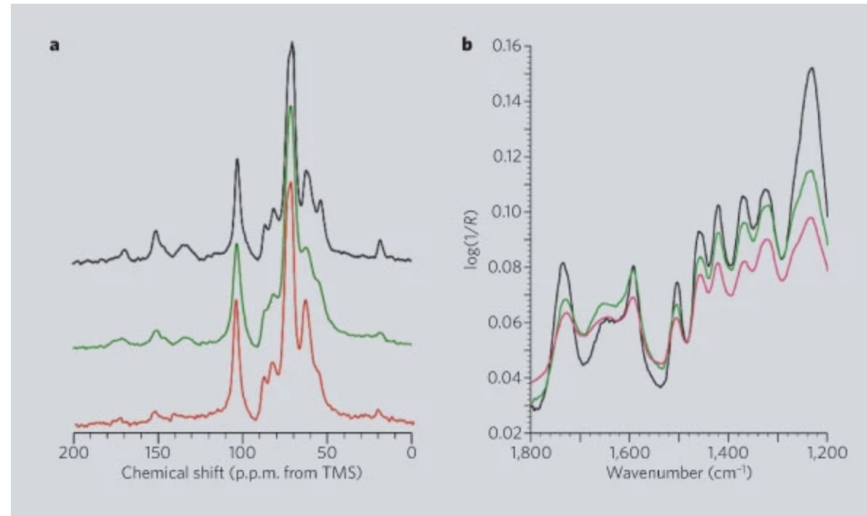
Fig. 1. *Planck* 2018 temperature power spectrum. At multipoles $\ell \geq 30$ we show the frequency-coadded temperature spectrum computed from the P11k cross-half-mission likelihood, with foreground and other nuisance parameters fixed to a best fit assuming the base- Λ CDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the Commander component-separation algorithm, computed over 86% of the sky. The base- Λ CDM theoretical spectrum best fit to the *Planck* TT,TE,EE+lowE+lensing likelihoods is plotted in light blue in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\sigma$ diagonal uncertainties, including cosmic variance (approximated as Gaussian) and not including uncertainties in the foreground model at $\ell \geq 30$. Note that the vertical scale changes at $\ell = 30$, where the horizontal axis switches from logarithmic to linear.

Planck
(2018)

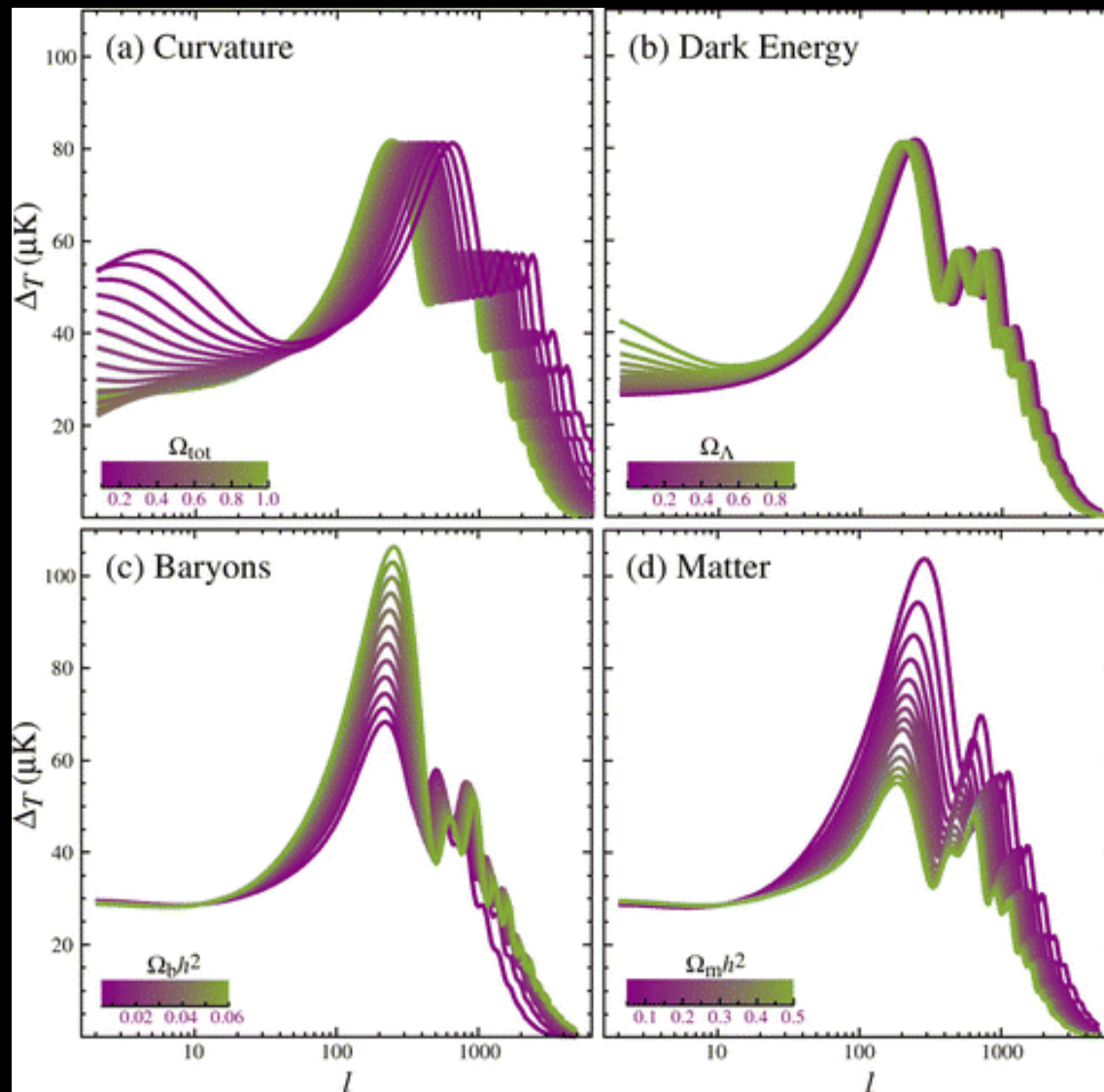
This kind of spectrum has an interesting analogy.....

Figure 1: Spectroscopy of maple wood samples from antique violins.

From: [Wood used by Stradivari and Guarneri](#)



a, ^{13}C solid-state NMR spectra. TMS, tetramethylsilane standard. **b**, Attenuated total reflection Fourier-transform infrared spectra. Black trace, recent untreated Bosnian maple; green, violin of Stradivari; red, violin of Guarneri del Gesu. Conditions and statistical analysis are described in [supplementary information](#).



http://map.gsfc.nasa.gov/resources/camb_tool/index.html

Determination of Λ CDM parameters (from CMB)

Parameter	TT	TE	EE	TTTEEE
$\Omega_b h^2$	0.02224 ± 0.00025	0.02238 ± 0.00020	0.02283 ± 0.00081	0.02226 ± 0.00013
$\Omega_c h^2$	0.1183 ± 0.0024	0.1172 ± 0.0017	0.1169 ± 0.0035	0.1188 ± 0.0012
$100\theta_*$	1.04123 ± 0.00046	1.04151 ± 0.00041	1.04001 ± 0.00059	1.04108 ± 0.00026
$\log(10^{10} A_s)$	3.073 ± 0.061	3.030 ± 0.028	3.077 ± 0.039	3.040 ± 0.014
n_s	0.9678 ± 0.0072	0.9689 ± 0.0091	0.9797 ± 0.0110	0.9681 ± 0.0039
τ	0.0753 ± 0.0322	0.0572 ± 0.0065	0.0582 ± 0.0066	0.0580 ± 0.0062
H_0	67.89 ± 1.11	68.49 ± 0.76	68.49 ± 1.91	67.64 ± 0.52
σ_8	0.8186 ± 0.0221	0.7973 ± 0.0129	0.8149 ± 0.0189	0.8070 ± 0.0065
S_8	0.826 ± 0.024	0.795 ± 0.021	0.814 ± 0.044	0.819 ± 0.014
Ω_m	0.3059 ± 0.0147	0.2983 ± 0.0099	0.2995 ± 0.0226	0.3092 ± 0.0070

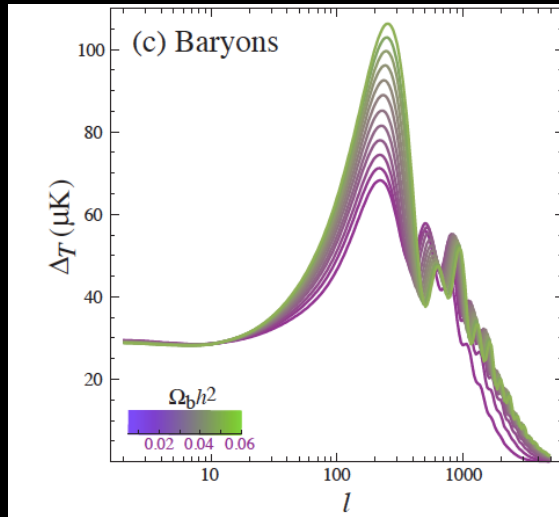
Table 3: Parameter constraints in the 6-parameter Λ CDM model for each data set and their combination, using HiLLiPoP V4.2 in addition to Commander and LoLLiPoP at low ℓ . We report mean values and symmetrical 68 % confidence intervals.

Planck collaboration 2023, (arXiv 2309.10034)

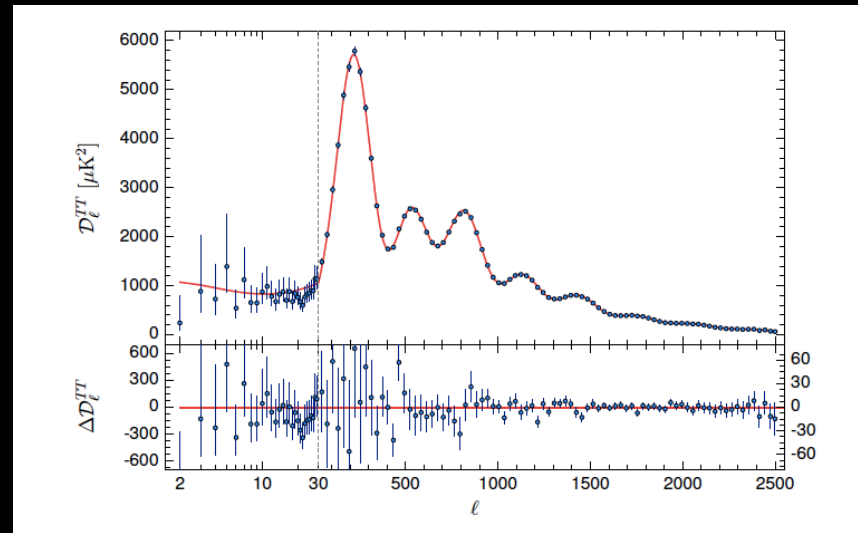
CMB data clearly show that in addition to a standard baryonic matter component, we also need some non-standard cold dark matter component

Baryon asymmetry of the universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2018, 1807.06209)



(CMB+BAO)

$$\Omega_{B0} h^2 = 0.02242 \pm 0.00014$$

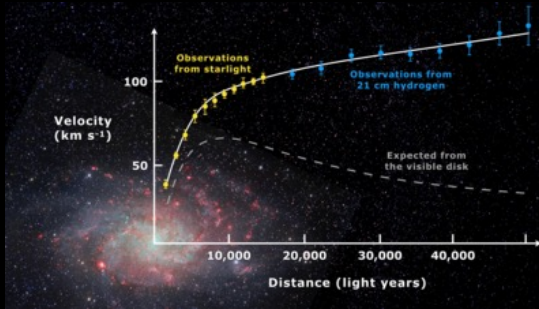
$$\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5 \Omega_{B0} h^2 \times 10^{-10} = (6.12 \pm 0.04) \times 10^{-10} = \eta_{B0}^{CMB}$$

- Consistent with (older) BBN determination but more precise and accurate
- Today the asymmetry coincides with the matter abundance since there is no evidence of primordial antimatter
- Even though all 3 Sakharov conditions are satisfied in the SM, any attempt to reproduce the observed value fails by many orders of magnitude $\Rightarrow$ it requires NEW PHYSICS!

Dark Matter

At the present time dark matter acts as a cosmic glue keeping together

stars in galaxies and



galaxies in clusters of galaxies

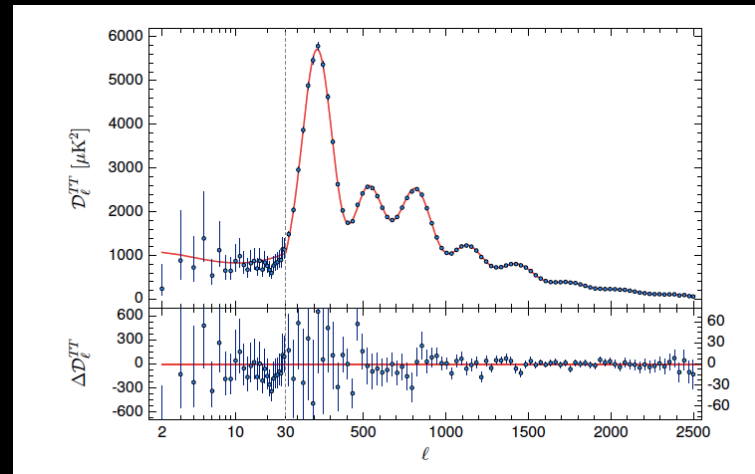
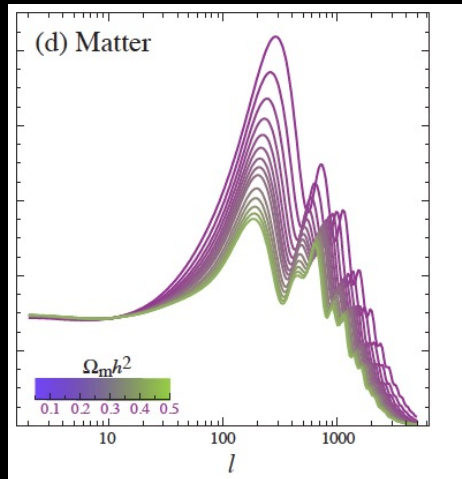


Coma cluster



bullet cluster

...but it also needs to be primordial to understand structure formation and CMB anisotropies



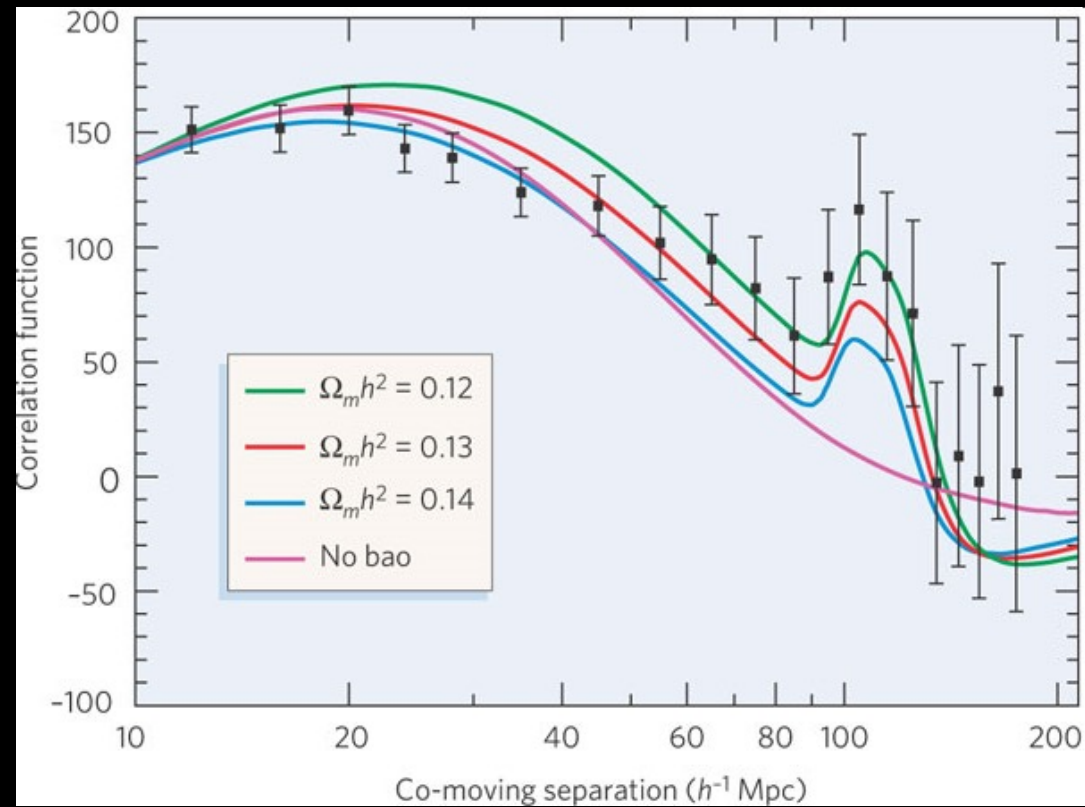
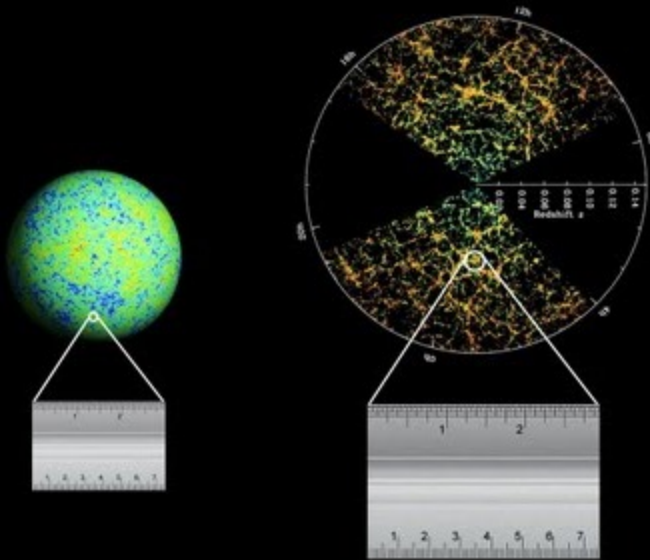
CMB +
BAO

(Planck 2018, 1807.06209)

(Hu, Dodelson, astro-ph/0110414)

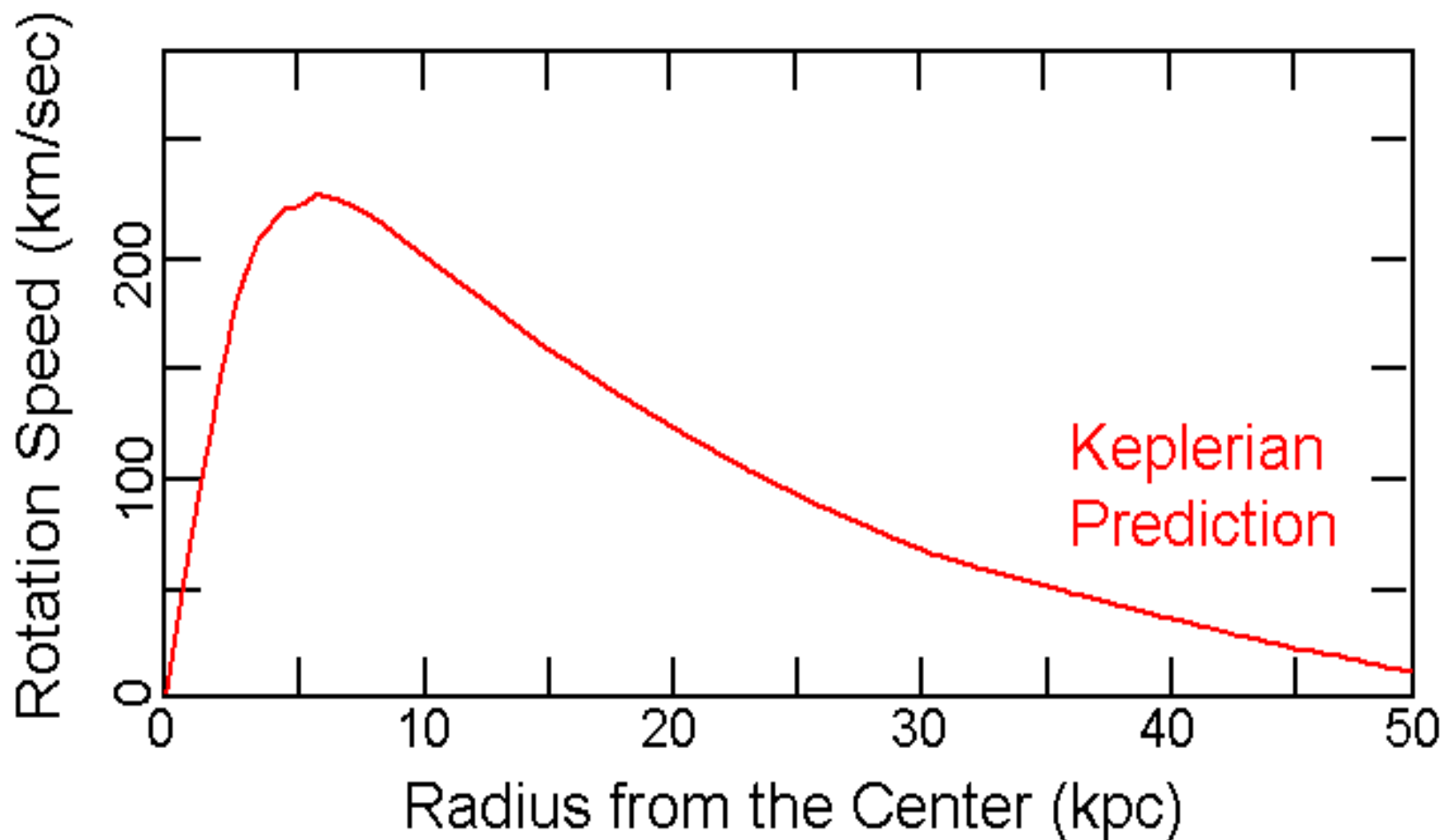
$$\Omega_{CDM,0} h^2 = 0.11933 \pm 0.0009 \sim 5 \Omega_{B,0} h^2$$

Baryon acoustic oscillations

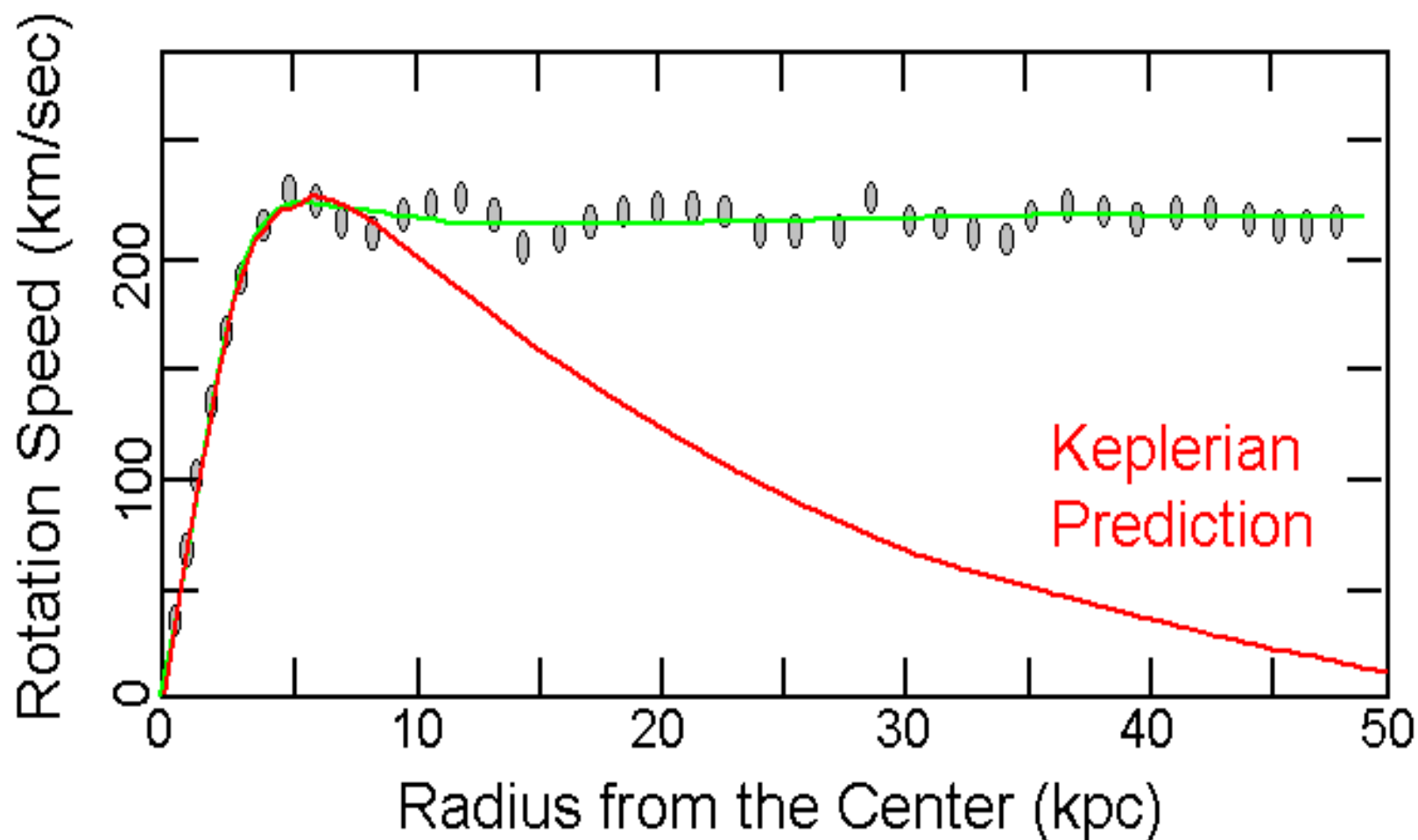


Direct determination of the
(total) matter component

Observed vs. Predicted Keplerian



Observed vs. Predicted Keplerian



A Galaxy within its Dark Matter halo

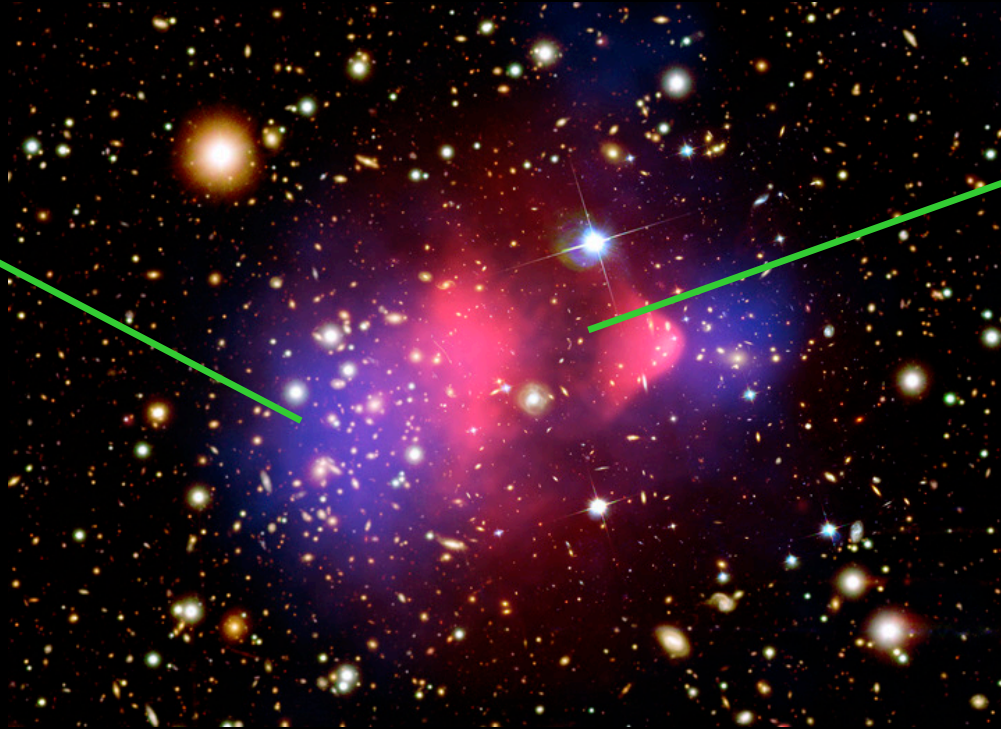


Coma cluster



'Bullet cluster': a direct evidence of Dark Matter

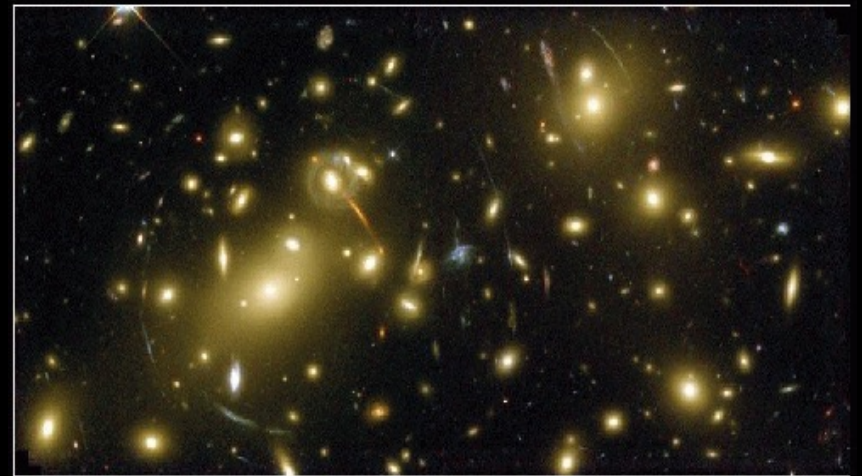
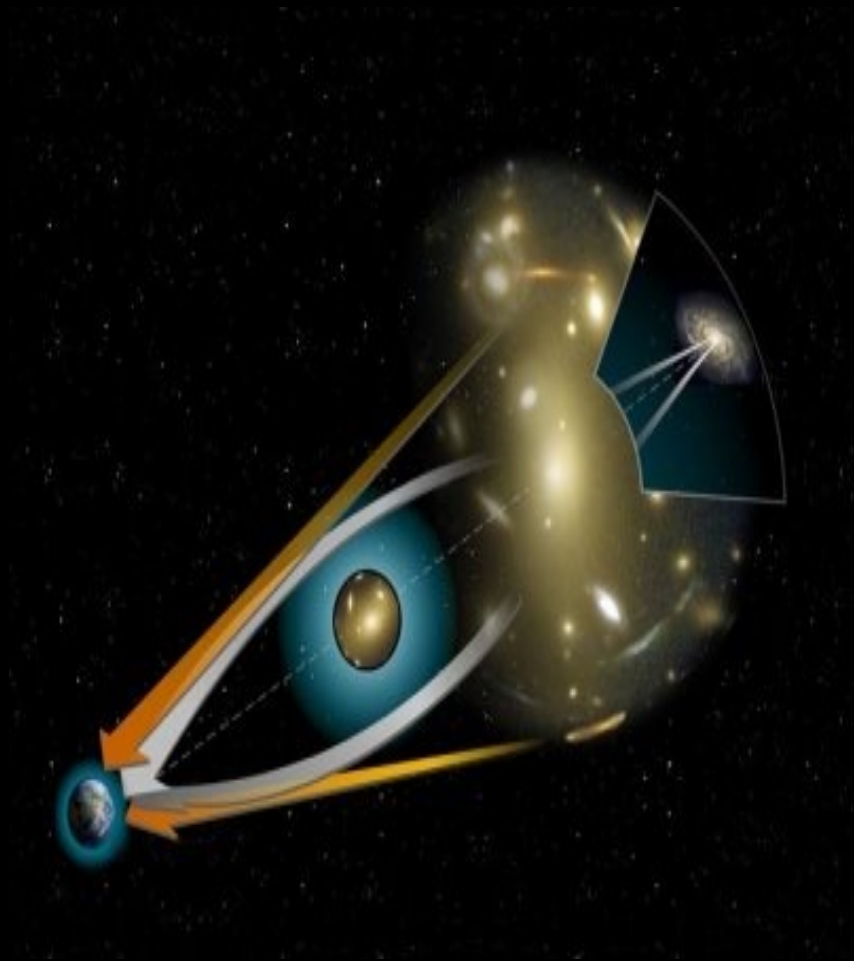
Dark Matter
from
gravitational
lensing



Hot gas from
X-ray
observations

Evidence of dark matter

Gravitational Lensing



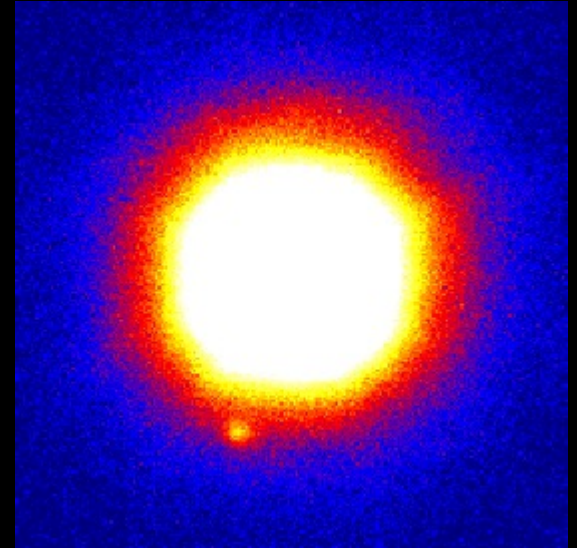
Galaxy Cluster Abell 2218

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

HST • WFPC2

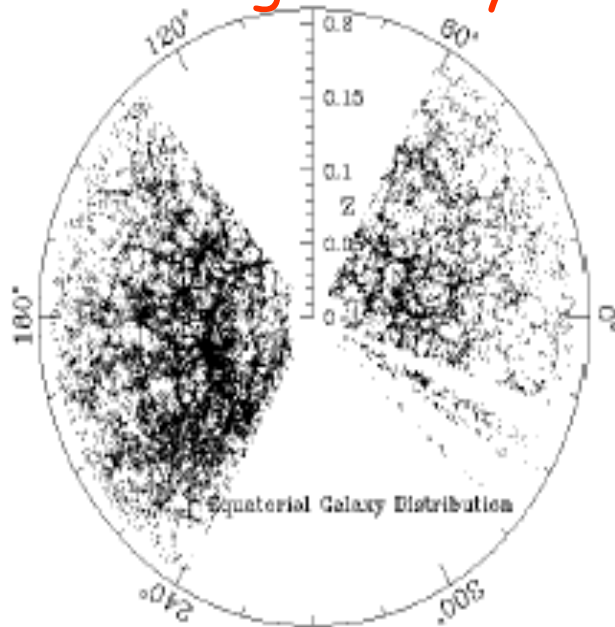
Non-baryonic dark matter component

- Compact Objects
 - E.g. planets and brown dwarfs
 - However, unlikely to be total source of mass inferred from interpolation.
 - Also unlikely for all "missing mass" to be baryonic because of Big Bang Nucleosynthesis and CMB anisotropies

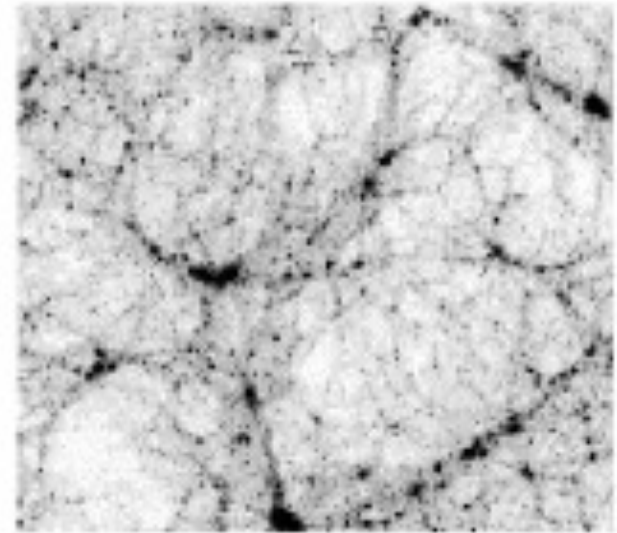


Galaxy distribution

The Universe observed:
Sloan Digital Sky Survey

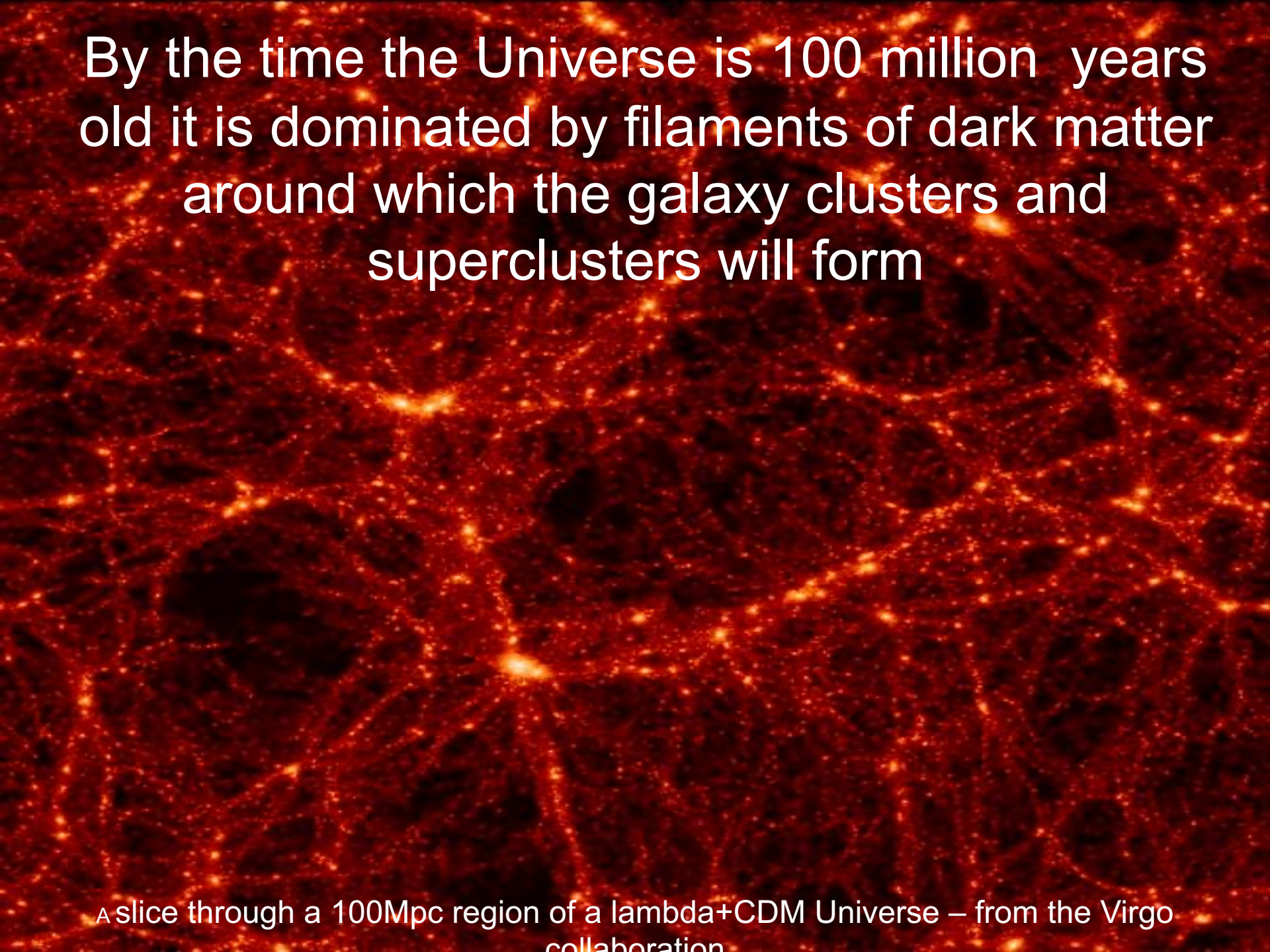


The Universe simulated :



Open problems:

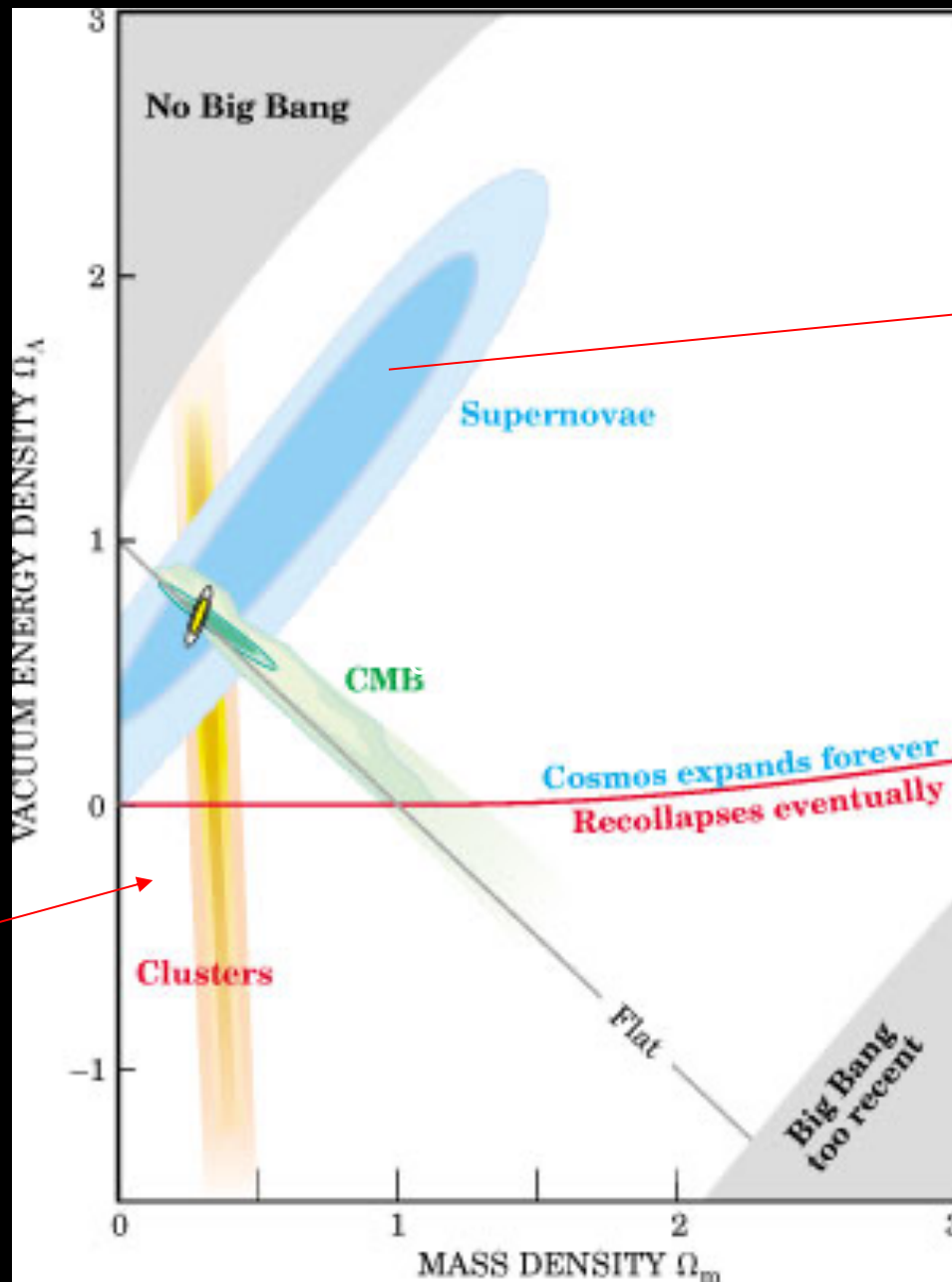
- **cusps** (too much Dark Matter in halo centers ?)
- **Halo substructure issues** (too many satellite galaxies ?)
- **Halo and galaxy merging** (too much galaxy merging ?)

The background image is a detailed simulation of the universe's large-scale structure. It features a dense, interconnected network of glowing orange and yellow filaments, representing dark matter, against a dark red background. These filaments form a complex web, with brighter, more concentrated regions indicating the formation of galaxy clusters and superclusters. The overall appearance is that of a cosmic web or a sponge-like structure, characteristic of the Lambda-CDM model of the universe.

By the time the Universe is 100 million years old it is dominated by filaments of dark matter around which the galaxy clusters and superclusters will form

A slice through a 100Mpc region of a Λ +CDM Universe – from the Virgo collaboration

"Cosmic Concordance"



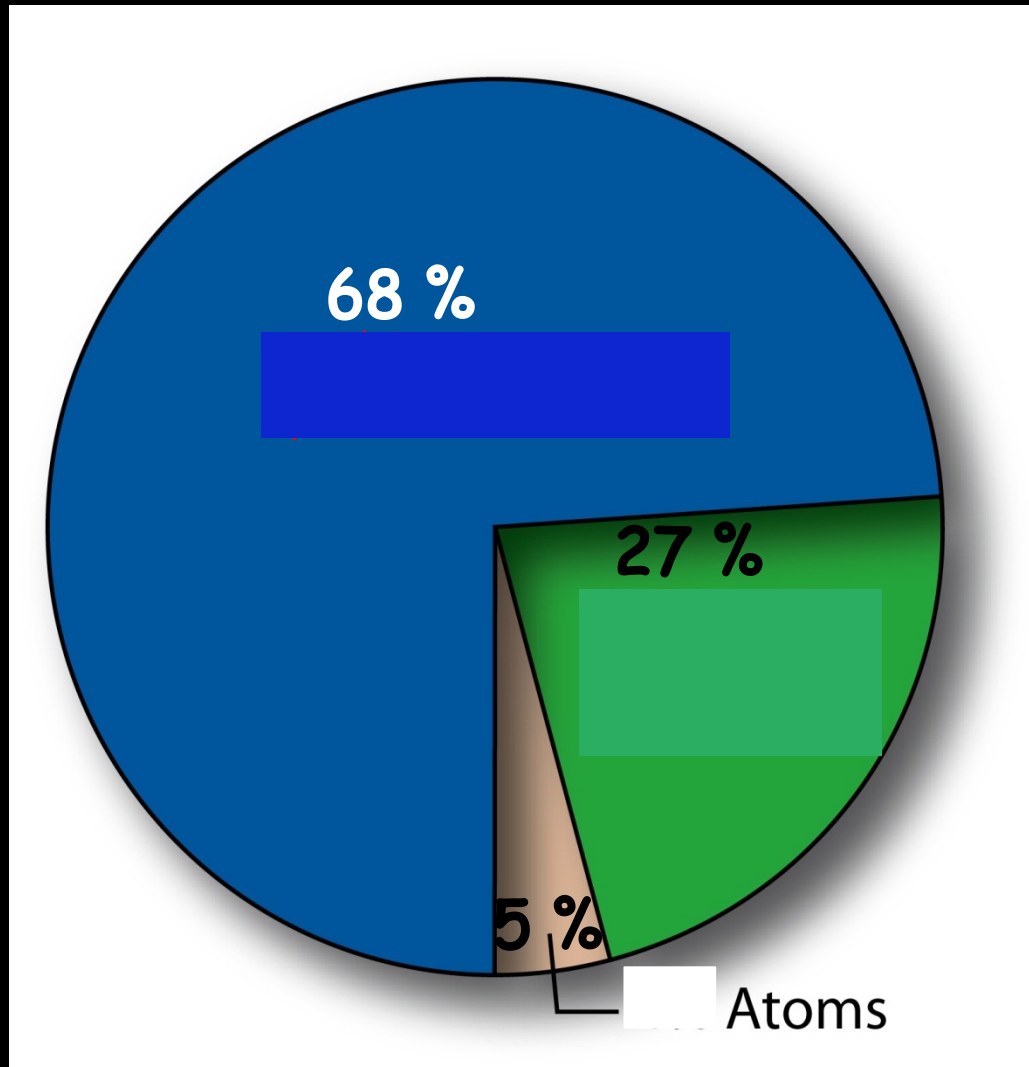
$$\Omega_{\Lambda,0} \simeq 1.5 \Omega_{M,0} + 0.25$$

Galaxy Surveys
(Dark Matter)

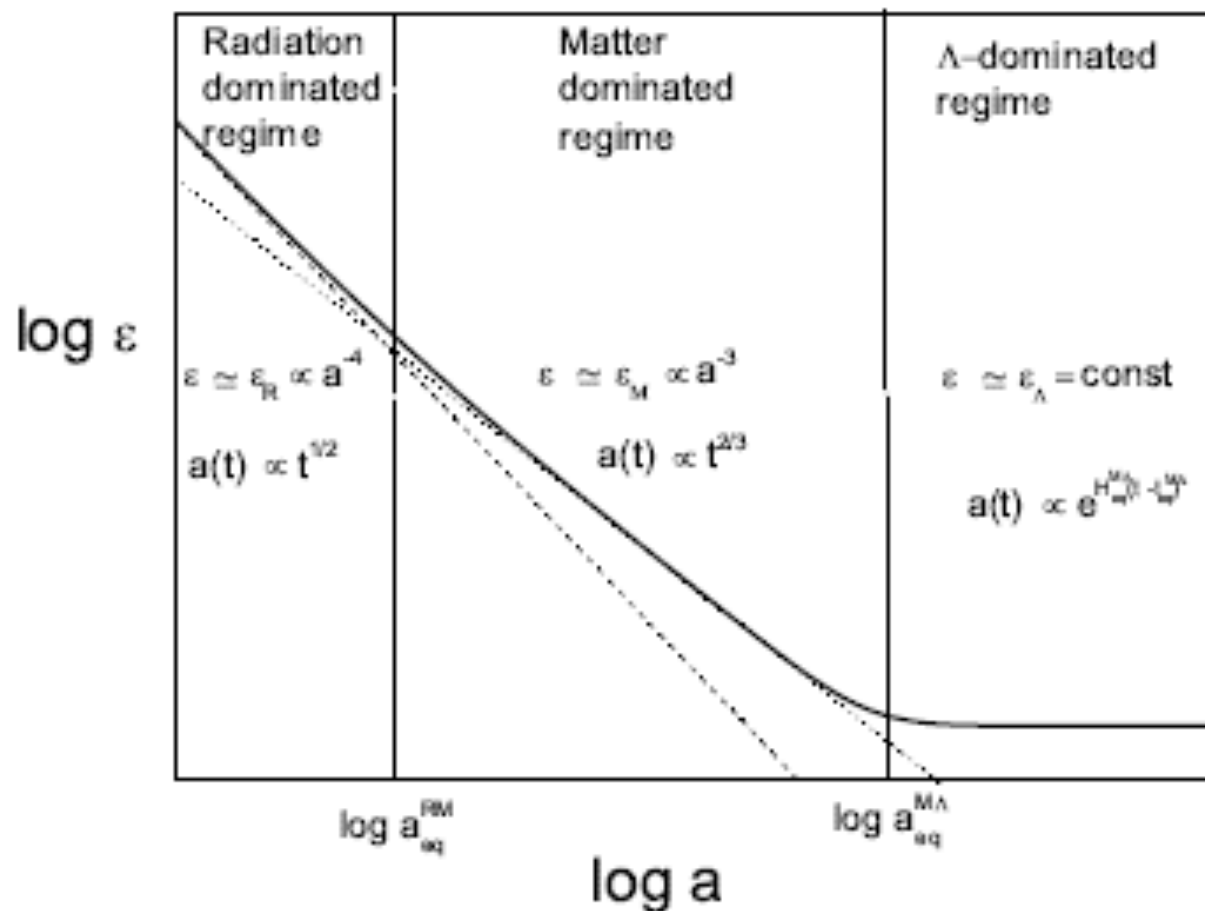
The matter-energy budget in the Λ CDM model at t_0

Atoms only make up 5% of the mass of the Universe

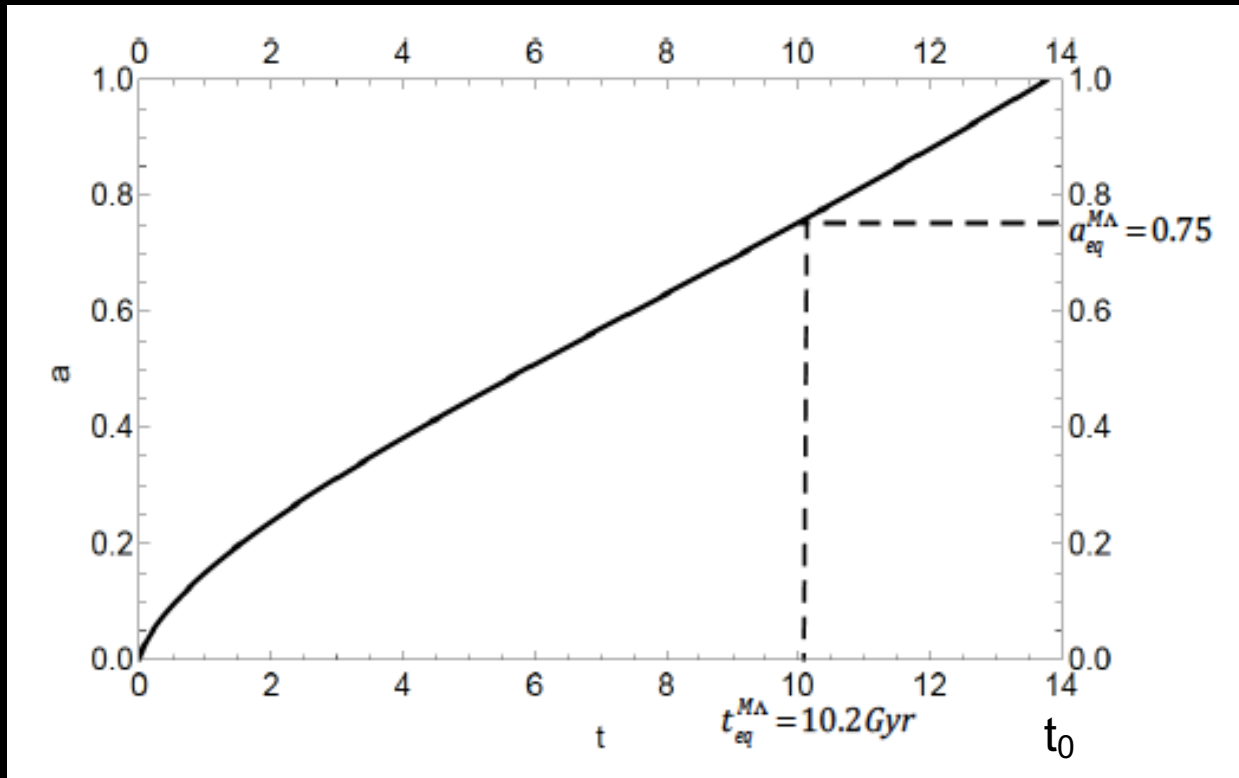
The rest is unknown Dark Energy (fluid like) and Dark Matter (particle like)



Flat Radiation-Matter- Λ model



Age of the universe in the Λ CDM model



$$\Omega_{\Lambda 0} = 0.692$$

$$\Omega_{M 0} = 0.308$$

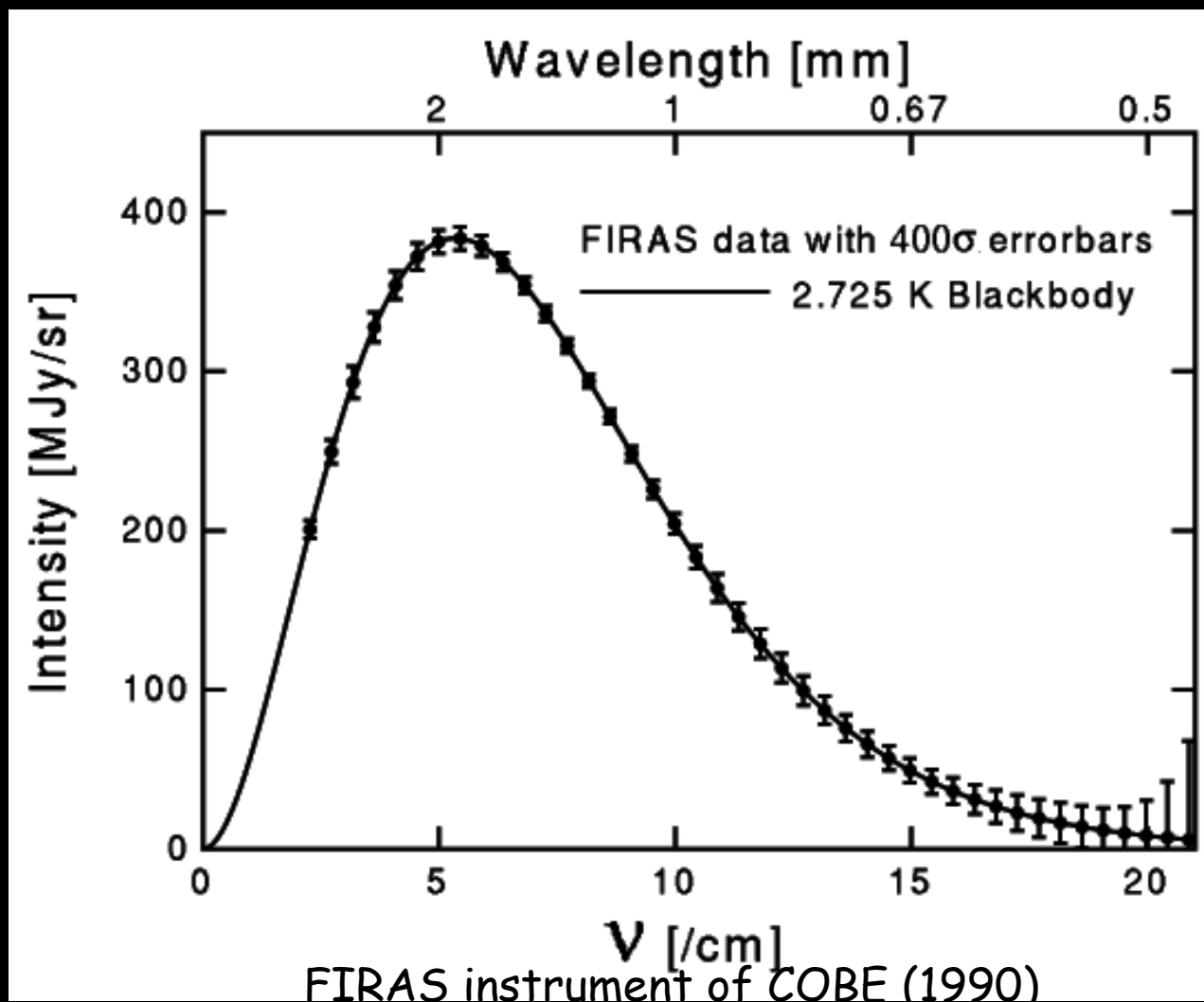
$$H_0^{-1} = 14.4 \text{ Gyr}$$

$$t_0 = \frac{2 H_0^{-1}}{3 \sqrt{\Omega_{\Lambda 0}}} \ln \left[\frac{1 + \sqrt{\Omega_{\Lambda 0}}}{\sqrt{1 - \Omega_{\Lambda 0}}} \right] \simeq 13.8 \text{ Gyr}$$

Thermal equilibrium in the early Universe

Thermal equilibrium of cosmic microwave background radiation

$$T_{\gamma 0} = (2.725 \pm 0.002) \text{ K} \quad n_{\gamma 0} \simeq 411 \text{ cm}^{-3}$$



Matter-Radiation decoupling

In general:

$$\frac{\Gamma}{H} \gtrsim 1 \Rightarrow \text{the process is switched on}$$

$$\frac{\Gamma}{H} \lesssim 1 \Rightarrow \text{the process is switched off}$$

A remarkable example: scattering Thompson (sort of matter-radiation "glue"):

$$\frac{\Gamma_{\text{Thompson}}}{H} \gtrsim 1 \Rightarrow T_{\gamma} > T_{\gamma}^{\text{dec}} \simeq 0.3 \text{ eV}$$

Photon Diffusion

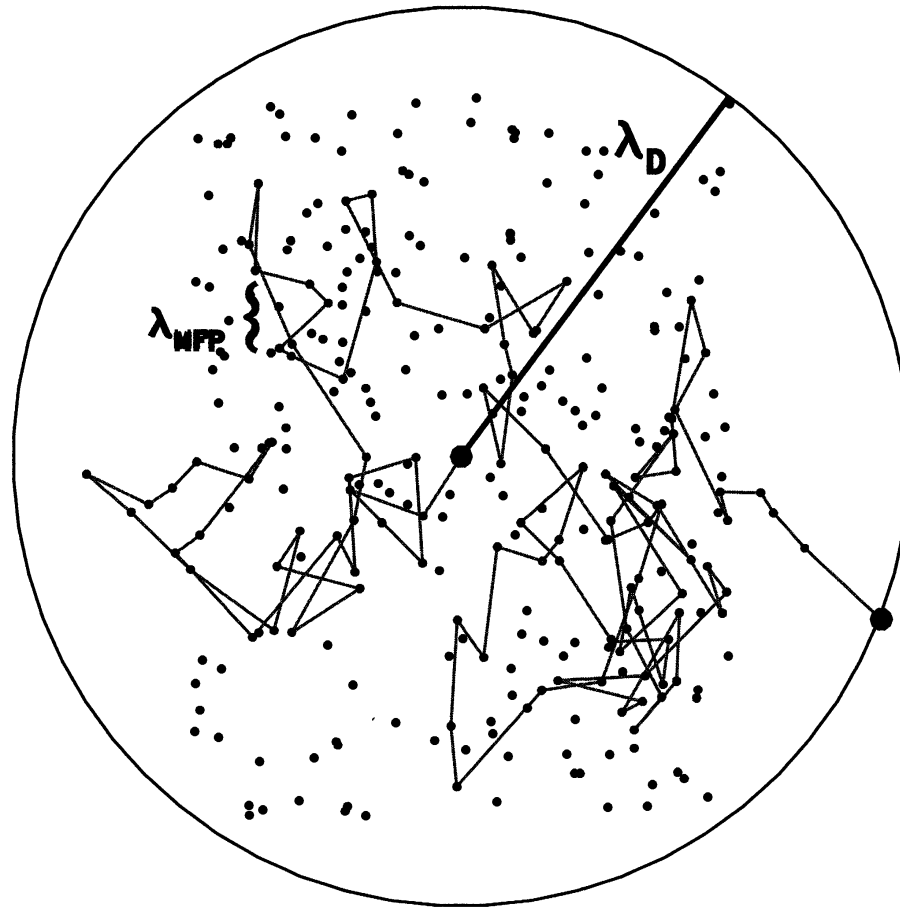
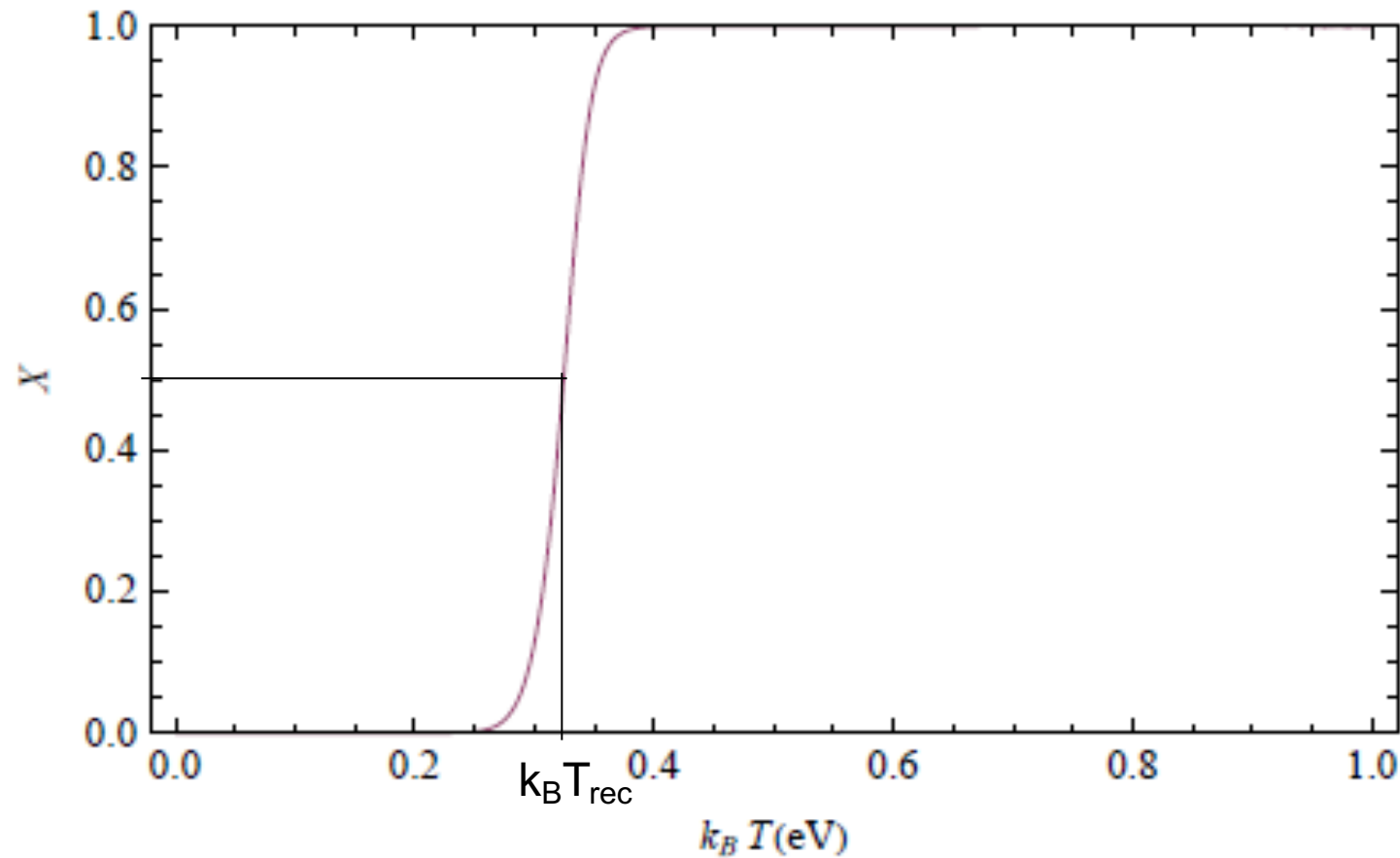
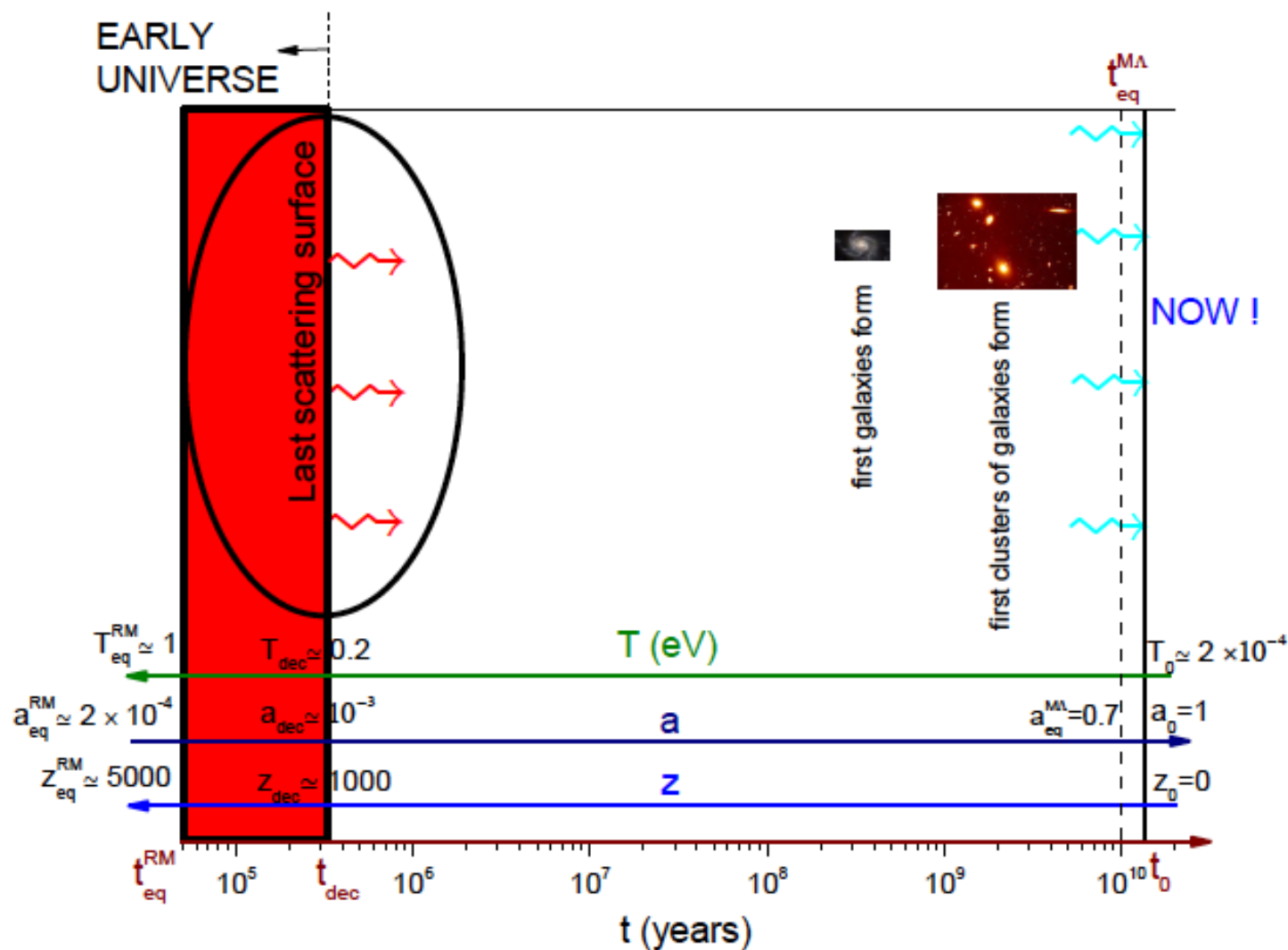


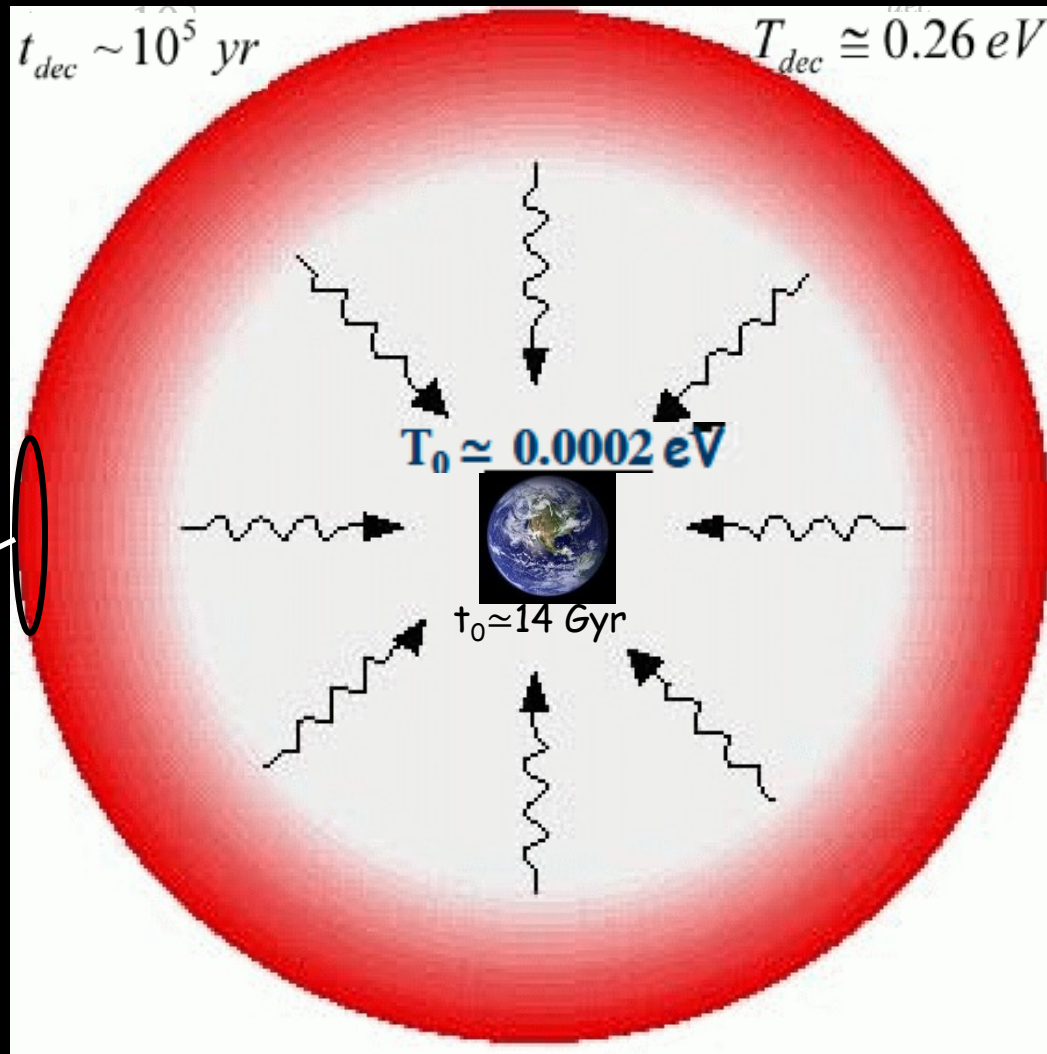
Figure 8.3. Photon diffusion through the electron gas. Electrons are denoted as points. Shown is a typical photon path as it scatters off electrons. The mean free path is λ_{MFP} . After a Hubble time, the photon has scattered many times, so that it has moved a distance of order λ_D .

Recombination: the fractional ionization vs. Temperature





Last scattering surface



See next slide

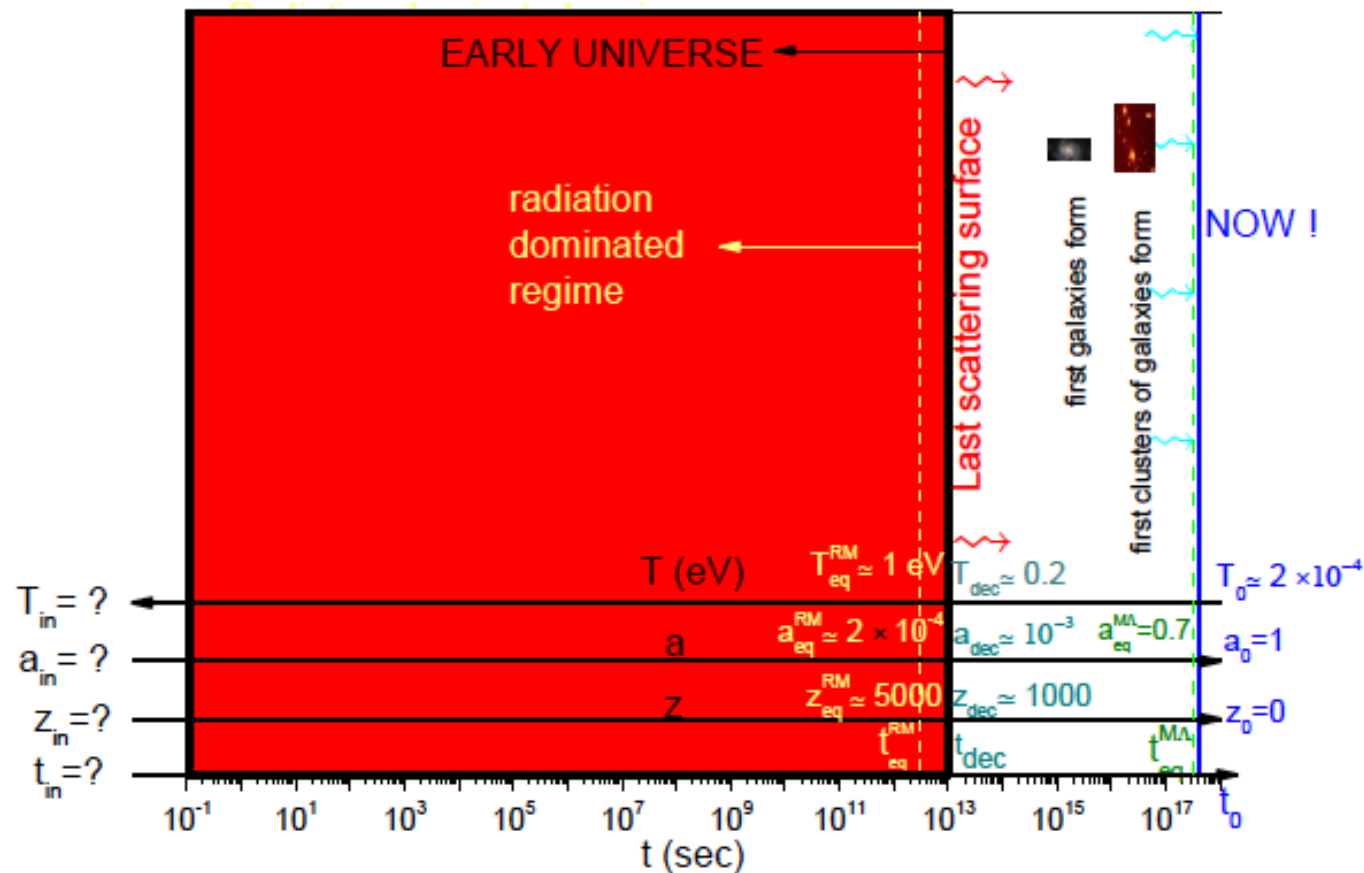
Matter-radiation equality in numbers

$$\frac{\varepsilon_{M0}}{a_{eq}^3} = \frac{\varepsilon_{R0}}{a_{eq}^4} \Rightarrow a_{eq} = \frac{\varepsilon_{R0}}{\varepsilon_{M0}} = \frac{\Omega_{R0}}{\Omega_{M0}} = \frac{0.90 \times 10^{-4}}{0.31} \simeq 2.9 \times 10^{-4}$$

$$z_{eq} = \frac{1}{a_{eq}} - 1 \simeq 3400$$

$$t_{eq} \simeq t_{eq}^{M\Lambda} \left(\frac{a_{eq}}{a_{eq}^{M\Lambda}} \right)^{\frac{3}{2}} \approx 50,000 \text{ yr}$$

History of The Early Universe



The Early Universe is for most of its history in a radiation dominated regime

$$H^2 = \frac{8\pi G}{3} \varepsilon_R,$$

$$\varepsilon_R = g_R \frac{\pi^2}{30} \frac{(k_B T)^4}{(\hbar c)^3}$$

$$T \gg m_{X_{b,f}} c^2/2,$$

$$g_R(T) \simeq \sum_{X_b} g_{X_b} + \frac{7}{8} \sum_{X_f} g_{X_f}$$

Number of
ultra-relativistic
degrees of freedom

$$H(T) = \sqrt{g_R} \sqrt{\frac{8\pi^3 G}{90}} T^2 \simeq 0.21 \sqrt{g_R} \left(\frac{k_B T}{\text{MeV}} \right)^2 s^{-1}.$$

$$t = \frac{1}{2 \sqrt{g_R} T^2} \sqrt{\frac{90}{8\pi^3 G}} \simeq \frac{2.4 \text{ s}}{\sqrt{g_R}} \left(\frac{\text{MeV}}{k_B T} \right)^2.$$

T_{dec}^ν

$$g_R(T \gtrsim 1 \text{ MeV}) = g_R^{\gamma+e^\pm+3\nu} = 2 + \frac{7}{8}(4 + 2 \times 3) = \frac{43}{4} = 10.75.$$

$\sim m_e$

$$g_R(k_B T \lesssim 0.5 \text{ MeV}) \simeq 2 + 3 \frac{7}{4} \left(\frac{4}{11} \right)^{4/3} \simeq 3.36.$$

Neutrino decoupling $\Rightarrow$ relic neutrinos !

$$\Rightarrow n_{\nu_\alpha}(T) = \frac{3}{4} \frac{\xi(3)}{\pi^2} g_\nu T^3 \text{ for } T \gtrsim T_{\nu_\alpha}^{\text{dec}}$$

$$\left. \frac{\Gamma_{\nu_{\text{weak}}}}{H} \right|_{T_{\nu_\alpha}^{\text{dec}}} \sim \left. \frac{n_{\nu_\alpha} \langle \sigma v \rangle}{H} \right|_{T_{\nu_\alpha}^{\text{dec}}} \sim \left. \frac{y_\alpha G_F^2 T^5}{\sqrt{2.8 g_R} \frac{T^2}{M_{\text{Pl}}}} \right|_{T_{\nu_\alpha}^{\text{dec}}} = 1 \Rightarrow T_{\nu_\alpha}^{\text{dec}} \simeq y_\alpha^{-\frac{1}{3}} 1.5 \text{ MeV}$$

number of
radiative degrees
of freedom

$$g_R \equiv \sum_{\text{bosons}} g_{X_b} + \frac{7}{8} \sum_{\text{fermions}} g_{X_f}$$

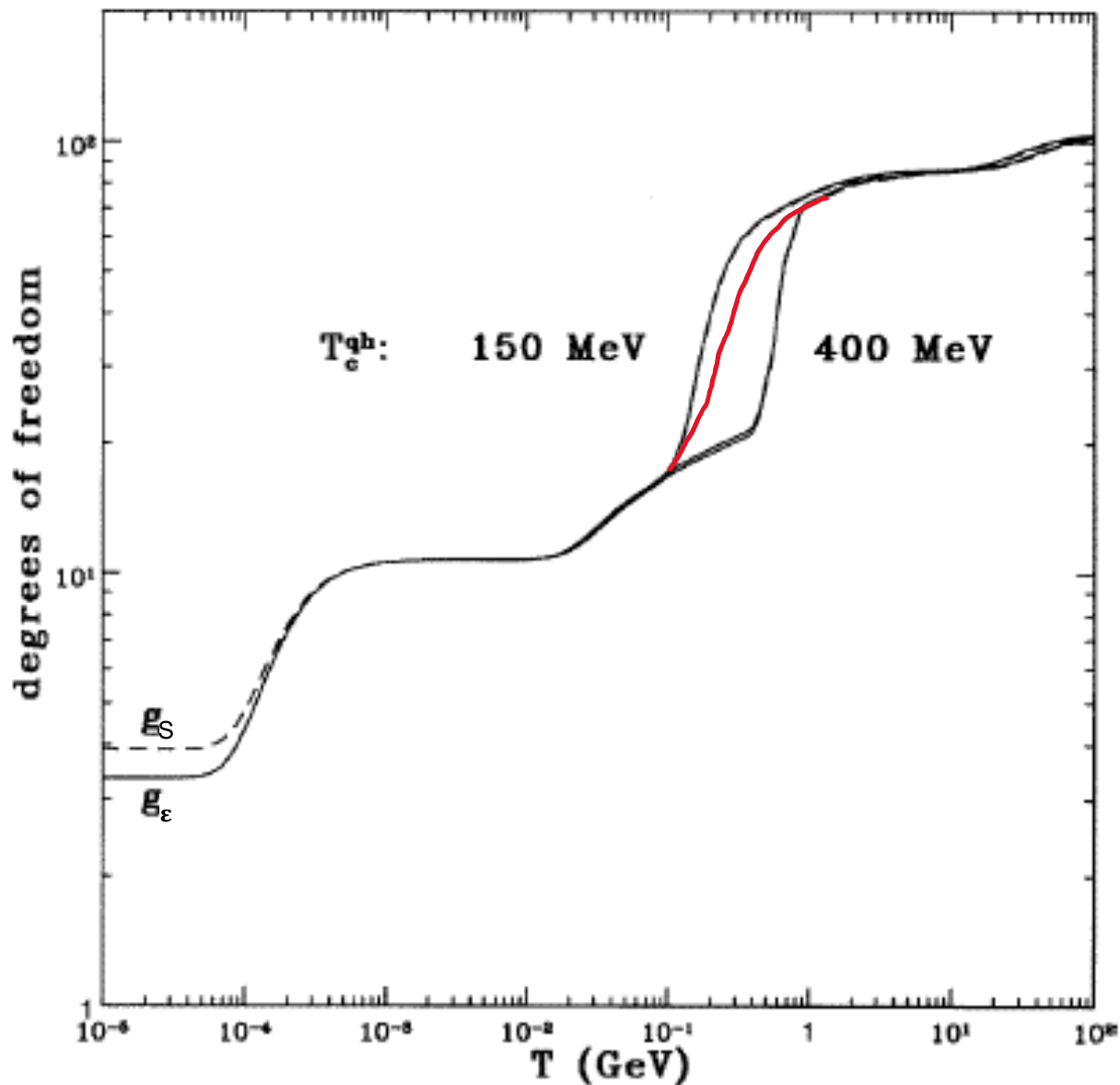
$\Rightarrow$

$$\rho = g_R \frac{\pi^2}{30} T^4$$

For $T < T_\nu^{\text{dec}}$ neutrinos are decoupled and their number in the comoving volume remains constant and one expects that at present there is a relic neutrino background together with CMBR with a temperature::

$$T_{\nu 0} \simeq \left(\frac{4}{11} \right)^{\frac{1}{3}} T_{\gamma 0} \simeq 1.96^0 K$$

Evolution of the number of ultra-relativistic degrees of freedom with temperature



Number of ultra-relativistic degrees of freedom vs. T

T	g_R	Particle content
$m_e c^2/2 \simeq 0.25 \text{ MeV} \gg T \geq T_0$	3.36	$\gamma + 3$ massless $\nu's$
$m_\mu c^2/2 \simeq 50 \text{ MeV} \gg T \gg m_e c^2/2$	$43/4 = 10.75$	$\dots + e^\pm$
$m_\pi c^2/2 \simeq 75 \text{ MeV} \gg T \gg m_\mu c^2/2$	$57/4 = 14.25$	$\dots + \mu^\pm$
$T_{\text{qh}} \simeq 150 \text{ MeV} \gg T \gg m_\pi c^2/2$	$69/4 = 17.25$	$\dots + \pi^0, \pi^\pm$
$m_\tau c^2/2 \gtrsim m_c c^2/2 \simeq 0.65 \text{ GeV} \gg T \gtrsim T_{\text{qh}}$	61.75	$\dots + \text{u,d,s quarks} + 8 \text{ gluons}$
$m_b c^2/2 \simeq 2 \text{ GeV} \gg T \gg m_\tau c^2/2$	75.75	$\dots + \tau^\pm + \text{c quark}$
$m_{W,Z,H^0} c^2/2 \simeq 40 \text{ GeV} \gg T \gg m_b c^2/2$	86.25	$\dots + \text{b quark}$
$m_t c^2/2 \simeq 90 \text{ GeV} \gg T \gg m_{W,Z,H^0} c^2/2$	96.25	$\dots + W^\pm, Z^0, H^0 \text{ bosons}$
$T \gg m_t c^2/2$	106.75	$\dots + \text{top quark}$

TABLE 13.1 Dependence of g_R on temperature in the standard model.

Extra (dark) radiation and number of effective neutrino species

Friedmann equation for the expansion rate:

$$H^2(t) = \frac{8\pi G}{3} \rho(t), \quad \rho(t) = \rho_R(t) + \rho_M(t)$$

Introduce the *number of ultra-relativistic degrees of freedom*:

$$\rho_R(T) = g_\rho(T) \frac{\pi^2}{30} T^4, \quad T = T(t)$$

$$\rho_R(T) = \rho_R^{SM}(T) + \Delta\rho_R(T) \Rightarrow g_\rho^{SM}(T) + \Delta g_\rho(T),$$

At temperatures $T \lesssim 10$ MeV (those probed by BBN and CMB):

$$g_\rho^{SM}(T) = 2 + \frac{7}{8} \left[4g_\rho^e(T) + 2N_\nu^{SM} \left(\frac{T_\nu}{T} \right)^4 \right], \quad N_\nu^{SM} \simeq 3.044$$

(e.g., 2012.02726)

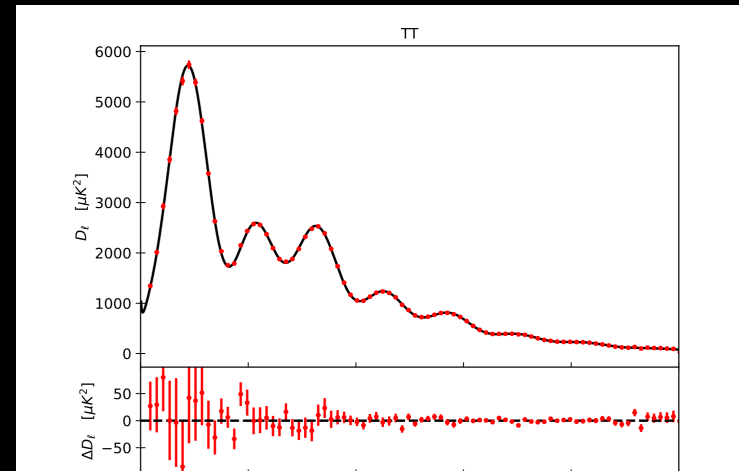
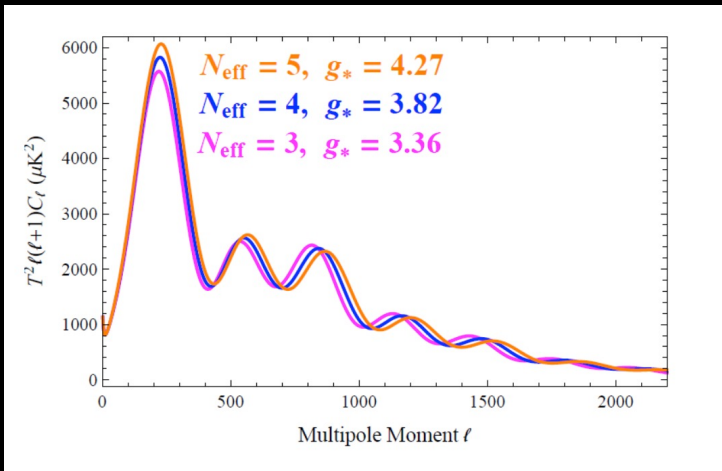
Analogously, we can parametrize the *number of extra u.r. d.o.f.* as:

$$\Delta g_\rho(T) = \frac{7}{4} \Delta N_\nu(t) \left(\frac{T_\nu}{T} \right)^4$$

Btw, from entropy conservation: $\frac{T_\nu}{T} = \left(\frac{2}{11} \right)^{\frac{1}{3}} \left[2 + \frac{7}{2} g_s^e(T) \right]^{\frac{1}{3}}$

Dark radiation at recombination

$$g_R^{\text{rec}} = 2 + N_\nu^{\text{rec}} \frac{7}{4} \left(\frac{T_{\nu 0}}{T_0} \right)^4 \simeq 3.36 + (N_\nu^{\text{rec}} - 3.044) \frac{7}{4} \left(\frac{T_{\nu 0}}{T_0} \right)^4$$



Planck 2023 (2309.10034)

From TT+TE+EE+lensing: $N_\nu^{\text{rec}} = 3.08 \pm 0.17 \Rightarrow$
 $\Delta N_\nu(t_{\text{rec}} \simeq 400,000 \text{ yr}) \lesssim 0.38$ (95% C. L.)

This proves the presence of neutrinos at recombination and also places a stringent upper bound on the amount of dark radiation $\Rightarrow$ strong constraints on BSM physics !



George Gamow
(1904-1968)

Big Bang Nucleosynthesis (BBN)

Assumption: $T_{in} > m_n - m_p \simeq 1.3 \text{ MeV}$

A strict **thermal equilibrium calculation** of the primordial nuclear abundances gives clear wrong predictions !

Saha equation

$$X_i = g_A C_A A^{\frac{5}{2}} \left(\frac{T}{m_N} \right)^{\frac{3(A-1)}{2}} \eta^{A-1} X_p^Z X_n^{A-Z} e^{\frac{B_i}{T}}$$

Nucleosynthesis temperature for the element " i "

$$\left[\frac{X_i(T_{\text{NUC}}^i)}{X_p^Z X_n^{A-Z}} \right]_{\text{eq}} \equiv 1$$

$\Rightarrow$

$$T_{\text{NUC}}^A = \frac{B_A / (A - 1)}{39 - (A - 1) \ln \eta_{10} - \ln(C_A) / (A - 1)}$$

the first element to be synthesized would be Helium 4 at

$$\left(\frac{X_n}{X_p} \right)_{\text{eq}} = \left(\frac{n_n}{n_p} \right)_{\text{eq}} \simeq e^{-\frac{1.3 \text{ MeV}}{T}},$$

$$T_{\text{NUC}}^4 \simeq 0.28 \text{ MeV}$$

$\Rightarrow$

$$Y_p^{\text{eq}} \sim 0.01$$

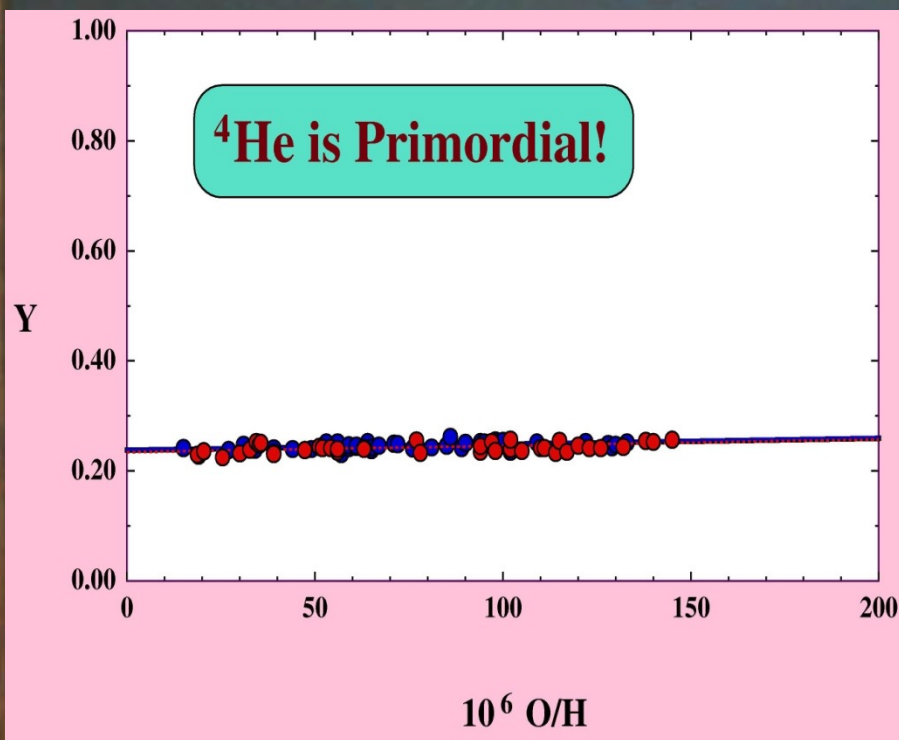
Primordial Nuclear Abundances

element $i \equiv (A, Z) \Rightarrow$ Nuclear abundances

$$X_i \equiv \frac{A n_i}{n_N},$$

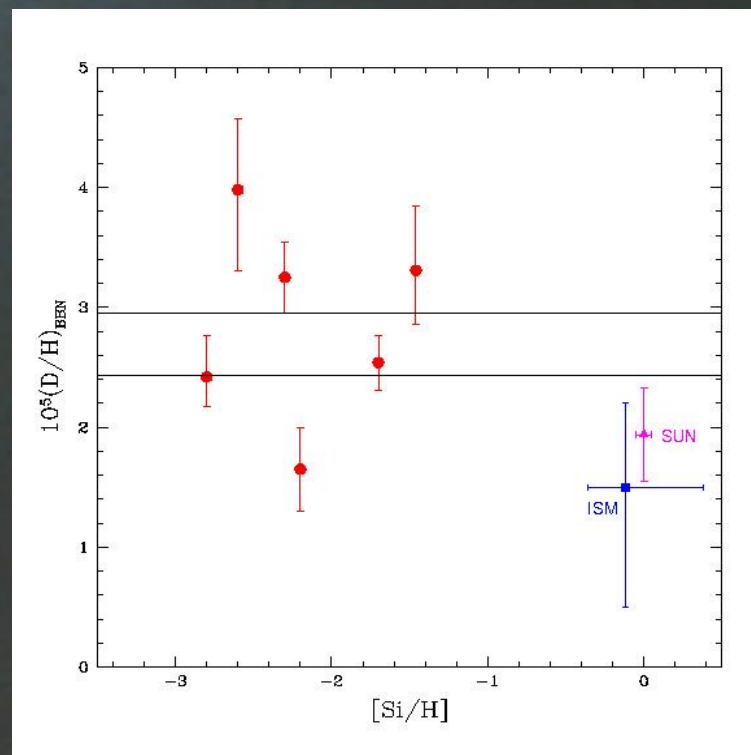
$$\sum_i X_i = 1$$

Extragalactic ^4He
Observations (H II Regions)



$$Y_p = 0.240 \pm 0.0006$$

D/H vs. Metallicity



$$(\text{D}/\text{H})_p = (2.68 \pm 0.27) \times 10^{-5}$$

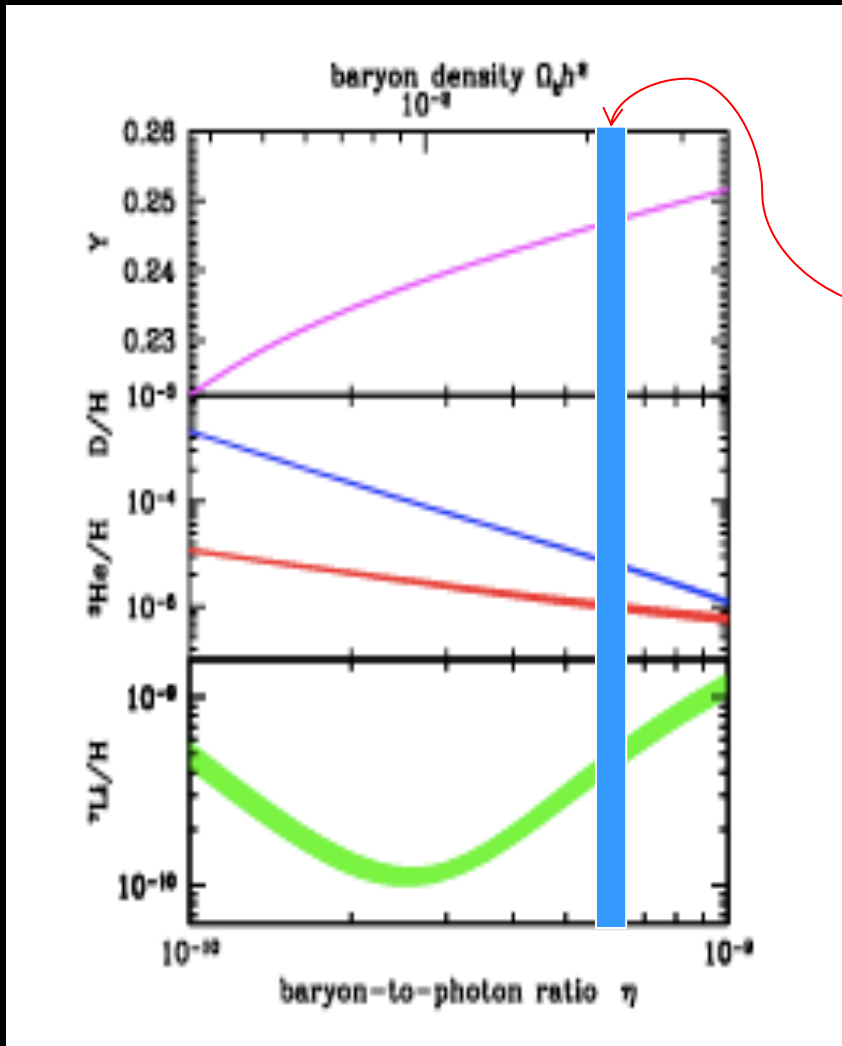
Big Bang Nucleosynthesis

Relevant nuclear processes

- 1) $p + n \leftrightarrow D + \gamma$
- 2) $D + n \leftrightarrow T + \gamma$
- 3) ${}^3\text{He} + n \leftrightarrow {}^4\text{He} + \gamma$
- 4) ${}^6\text{Li} + n \leftrightarrow {}^7\text{Li} + \gamma$
- 5) ${}^3\text{He} + n \leftrightarrow T + p$
- 6) ${}^7\text{Be} + n \leftrightarrow {}^7\text{Li} + p$
- 7) ${}^7\text{Li} + n \leftrightarrow {}^3\text{He} + {}^4\text{He}$
- 8) ${}^7\text{Be} + n \leftrightarrow {}^4\text{He} + {}^4\text{He}$
- 9) $D + p \leftrightarrow {}^3\text{He} + \gamma$
- 10) $T + p \leftrightarrow {}^4\text{He} + \gamma$
- 11) ${}^6\text{Li} + p \leftrightarrow {}^7\text{Be} + \gamma$
- 12) ${}^7\text{Li} + p \leftrightarrow {}^4\text{He} + {}^4\text{He}$
- 13) $D + {}^4\text{He} \leftrightarrow {}^6\text{Li} + \gamma$
- 14) $T + {}^4\text{He} \leftrightarrow {}^7\text{Li} + \gamma$
- 15) ${}^3\text{He} + {}^4\text{He} \leftrightarrow {}^7\text{Be} + \gamma$
- 16) $D + D \leftrightarrow {}^3\text{He} + n$
- 17) $D + D \leftrightarrow T + p$
- 18) $D + T \leftrightarrow {}^4\text{He} + p$
- 19) $D + {}^3\text{He} \leftrightarrow {}^4\text{He} + n$
- 20) ${}^3\text{He} + {}^3\text{He} \leftrightarrow {}^4\text{He} + p + p$
- 21) $D + {}^7\text{Li} \leftrightarrow {}^4\text{He} + {}^4\text{He} + n$
- 22) $D + {}^7\text{Be} \leftrightarrow {}^4\text{He} + {}^4\text{He} + p$

Big Bang nucleosynthesis (+CMB input)

(PDB hep-ph/0108182)



(Cyburt, Field, Olive, Yeh 1505.01076)

$$\eta_{B0} \simeq 273.5 \Omega_{B0} h^2 \times 10^{-10}$$

$$\Rightarrow \eta_{B0}^{(CMB)} = (6.08 \pm 0.06) \times 10^{-10}$$

Using this measurement of η_{B0} from CMB, from ${}^4\text{He}$ abundance (Y) one finds:

$$N_\nu(t_f \simeq 1s) = 2.9 \pm 0.3$$

$$\Rightarrow \Delta N_\nu(t_f \simeq 1s) \lesssim 0.45 \text{ (95\%)}$$

(Fields, Olive, Yeh, Young hep-ph/1912.01132)

And from Deuterium abundance:

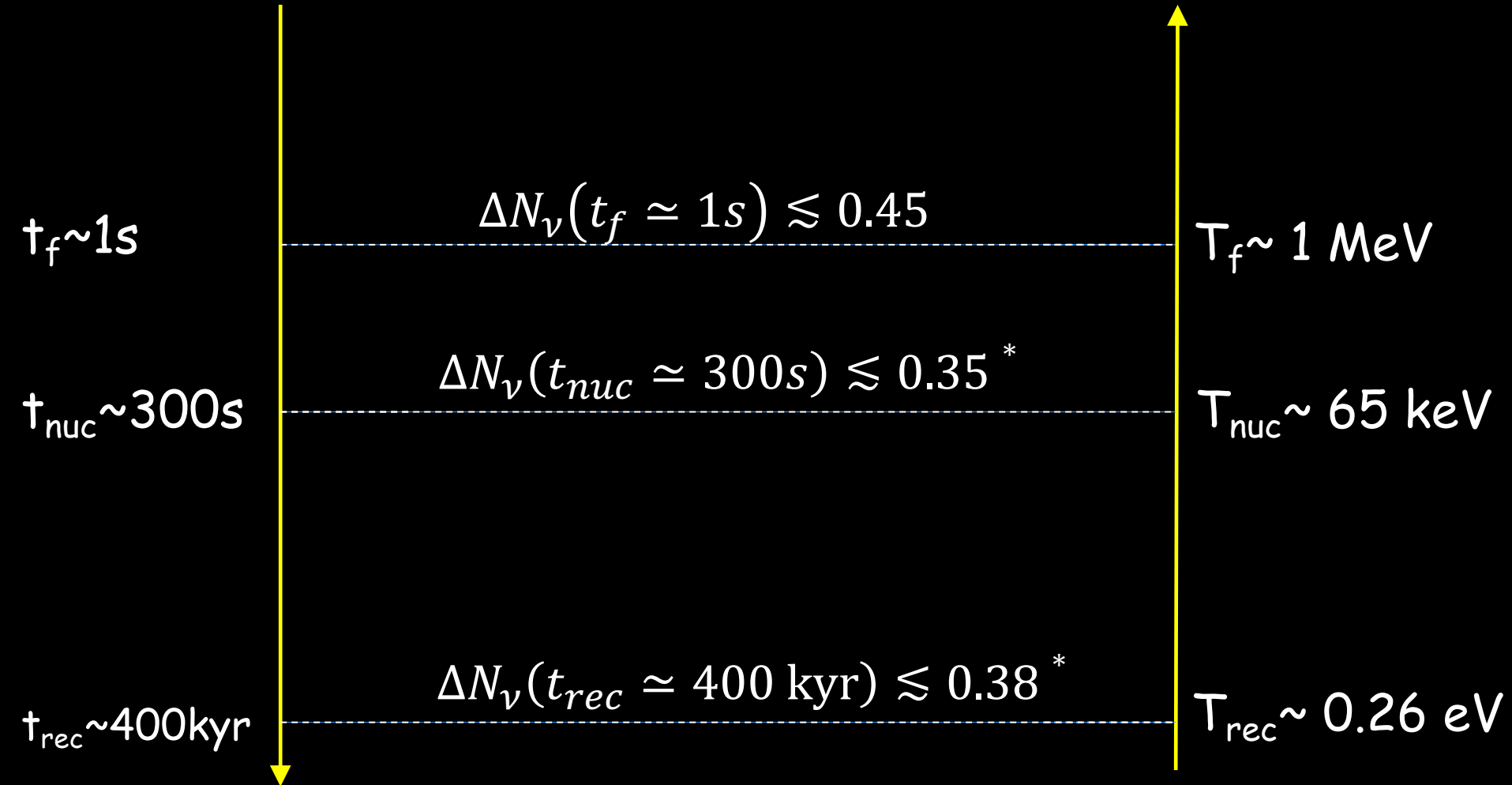
$$N_\nu(t_{nuc} \simeq 300s) = 2.95 \pm 0.22$$

$$\Rightarrow \Delta N_\nu(t_{nuc} \simeq 300s) \lesssim 0.4 \text{ (95\%)}$$

(Pisante, Mangano, Miele, Mazzella 2011.11537)

These results constrain **dark radiation** and show that $T_{RH} \gg T_v^{dec} \sim T_f \sim \text{MeV}$

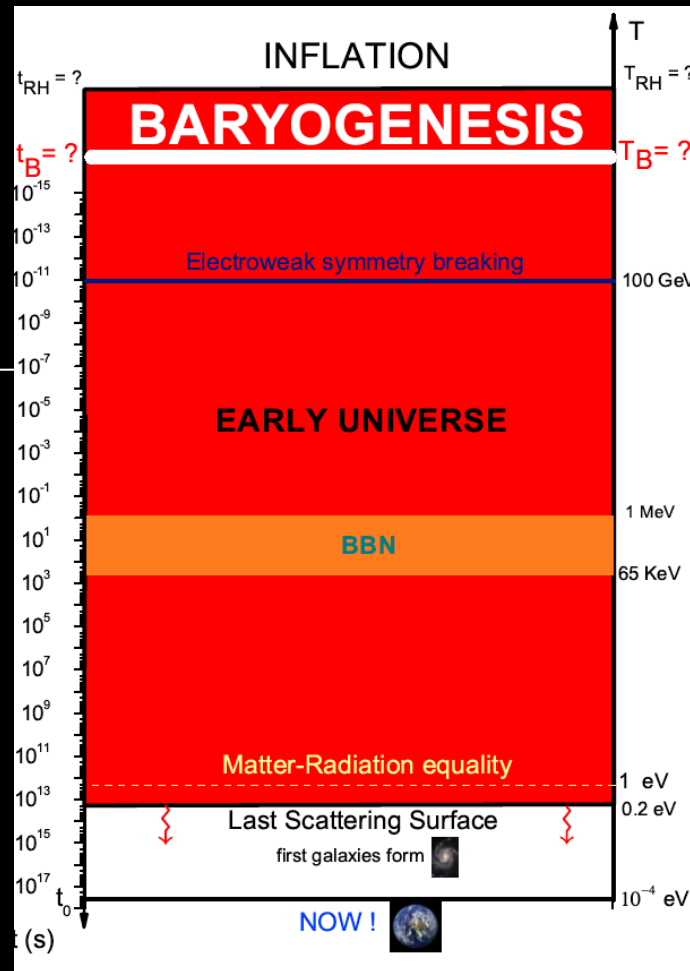
Summary of constraints on dark radiation



- A typical case corresponds to an injection (or freeze-out) at some high $T_* \gg T_f$: in that case $\Delta N_\nu(t_i) = \text{const}$
- **Example:** SM is augmented by 1 massless species X decoupling (in u.r. eq.) at $T_{X,f} = T_* \gg 100 \text{ GeV} \Rightarrow \Delta N_\nu \sim g_{\rho X^*} (4/7) (43/427)^{4/3} \sim 0.054 g_{\rho X^*}$

Cosmological puzzles

dark
matter
production



It is reasonable to think that the same extension of the SM necessary to explain neutrino masses and mixing might also address the cosmological puzzles:

- **Leptogenesis**,
- **RH neutrino as Dark matter**

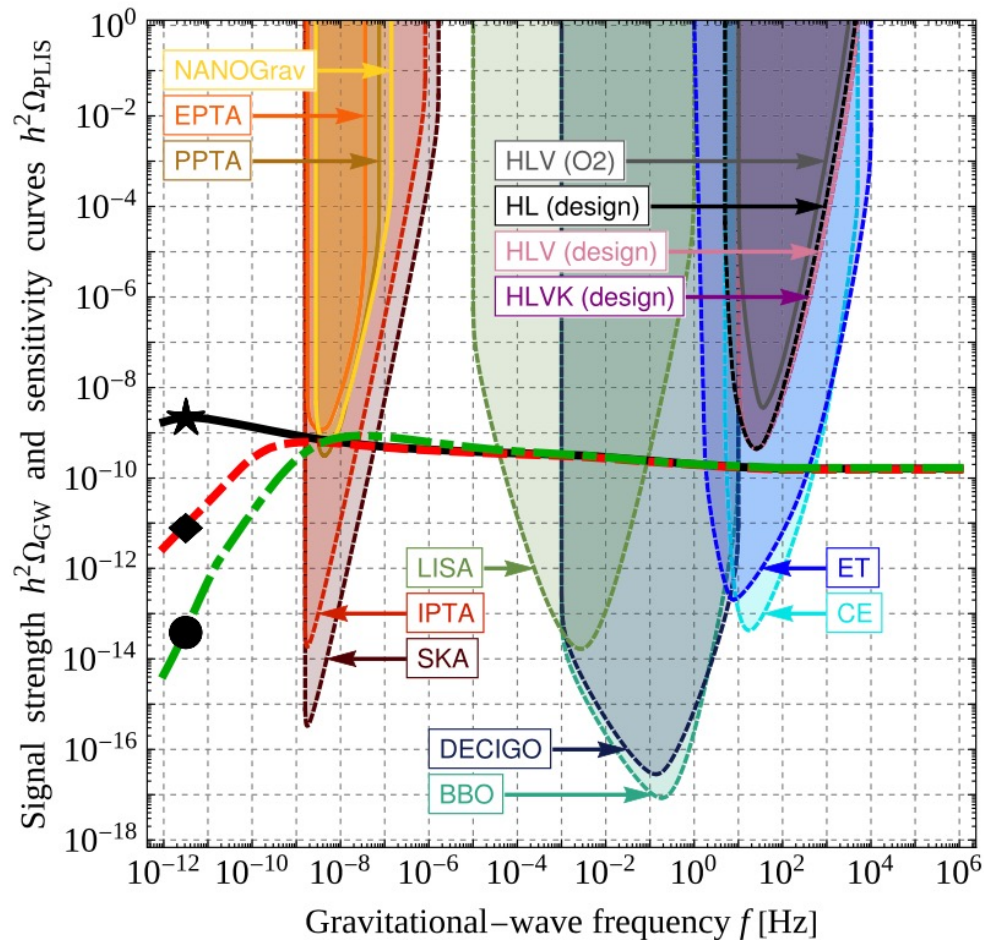
But many more exciting things are
happening in cosmology.....

Has NANOGrav Found First Evidence for Cosmic Strings?

Simone Blasi,^{1,*} Vedran Brdar,^{1,†} and Kai Schmitz^{2,‡}

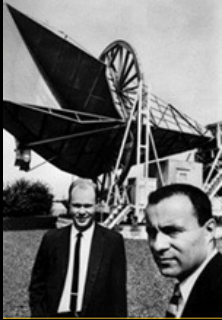
¹Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

²Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland



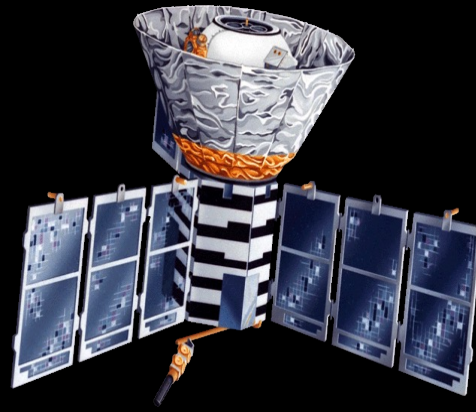
The excess radio
background mystery

The CMB spectrum: most perfect Planckian in nature



Penzias and Wilson (1965)

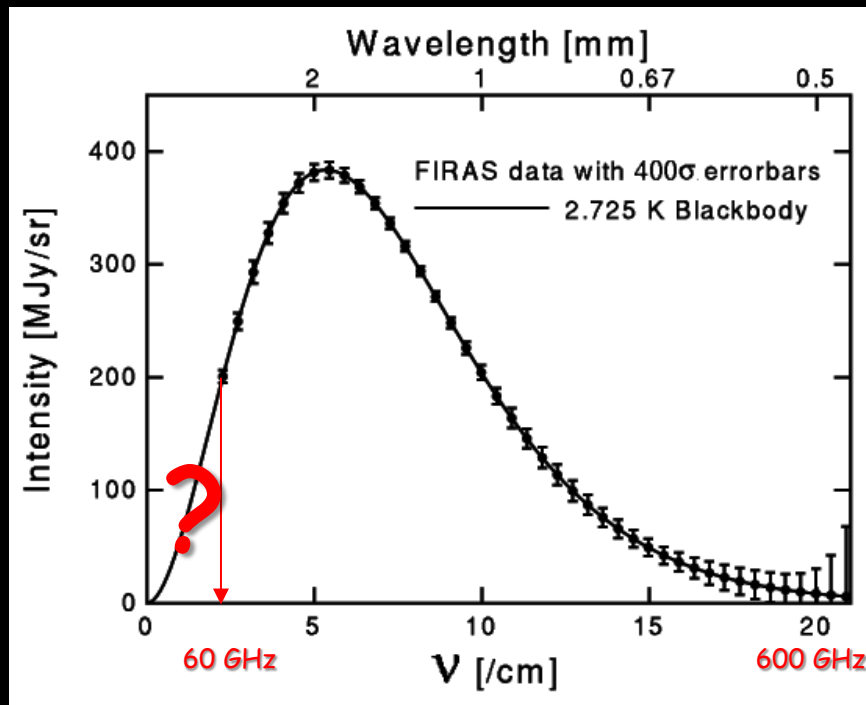
$$T_{\nu 0} = (3.5 \pm 1) \text{ }^{\circ}\text{K}$$



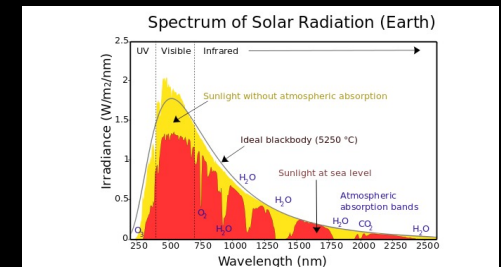
COBE satellite

FIRAS instrument of COBE (1990)

$$T_{\nu 0} = (2.725 \pm 0.001) \text{ }^{\circ}\text{K} \quad (\text{Fixsen and Mather 2002})$$



for a comparison

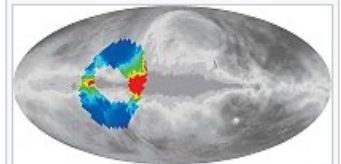
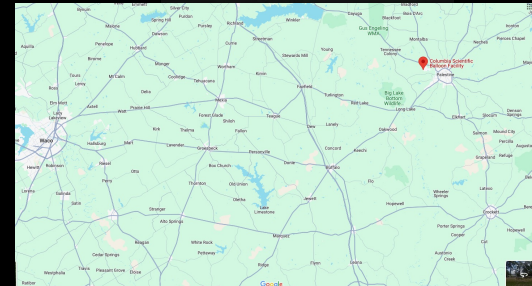


ARCADE 2: The 2006 FLIGHT

(Fixsen, Kogut, Levin, Limon, Lubin, Mirel, Seiffert, Singal, Wollack, Villela, Wuensche 0901.0555)



- Launched from Palestine TX (Columbia scientific balloon facility) on a 29 MCF balloon on 22 July 2006 at 1:15 UT
- It reached a float altitude of 37 km at 4:41 UT
- The entire gondola with the instrument was rotated so that 8.4% of the entire sky was observed
- The most useful observations were from 5:35 to 7:40 UT: **with only two hours of balloon flight observations, ARCADE 2 approaches the absolute accuracy of long-duration space missions**
- The uncertainty in the sky temperature is dominated by thermal gradients in the calibrator
- One main advantage of balloon flight is that at 37km the instrument is above about 99.7% of the atmosphere and an even larger fraction of water vapour and, second, it is well above the nearest source of any radio transmitters



ARCADE viewed about 7% of the sky. The observed region is colored on this all-sky radio map. The plane of our galaxy, the Milky Way, runs across the center.



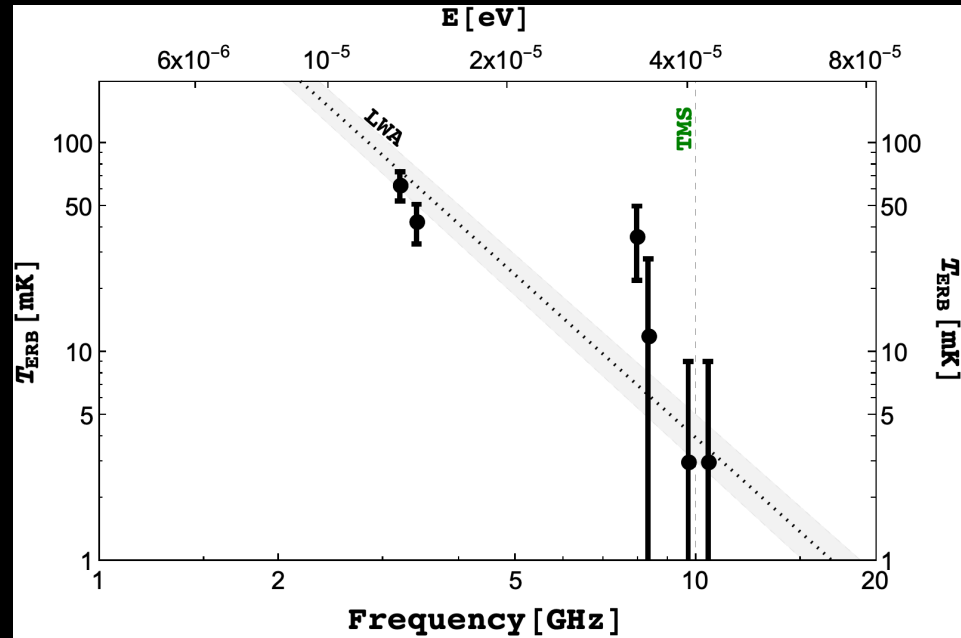
Photograph of the instrument upon landing, 2005. The electronics box and magnetometers which are mounted on the dewar are visible.

ARCADE 2: Results

(Fixsen, Kogut, Levin, Limon, Lubin, Mirel, Seiffert, Singal, Wollack, Villela, Wuensche 0901.0555)

$$T_{\text{ERB}} \equiv T_{\gamma 0}(\nu) - T_{\text{CMB},0}$$

↓
effective temperature



(Figure courtesy of Rishav Roshan)

- The ARCADE 2 measurement of the CMB temperature is in excellent agreement with the FIRAS instrument above 10 GHz
- Below 10 GHz, the detected radio background is brighter than expected ($\sim 5\sigma$ deviation)
- The Long Wavelength Array (LWA) measured the diffuse radio background in the 40-80 MHz, also finding an excess. In combination with ARCADE 2 data, they find a good fit in terms of a power-law:

$$T_{\text{ERB}} = (30.4 \pm 2.6) \left(\frac{\nu}{310 \text{ MHz}} \right)^{-2.58 \pm 0.05} \text{ K.}$$

The excess radio background is a mystery

- Part of the excess is due to galactic synchrotron radiation but this galactic contamination is significantly below the measured excess. (N.Fornengo, R.A. Lineros, M. Regis, M. Taoso 1402.2218)
- The excess cannot be explained by known population of sources: they give a contribution to the effective temperature that is 3-10 times smaller than the measured one. (J. Singal et al. 1711.09979)
- Low-redshift populations of discrete extra-galactic radio sources have been also excluded by cross correlating data of the diffuse radio sky with matter tracers at different redshifts provided by galaxy catalogs and CMB lensing. (E.Todarello, et al. 2311.17641)
- Exotic astrophysical explanations have been proposed (supermassive black holes and star forming galaxies) but typically they tend to produce also other (unobserved) signals and more importantly the Australian Telescope Compact Array (ATCA) constrains the contribution to the excess of extended source with angular size below 2 arcmin: **the ERB is extremely smooth**. (T. Vernstrom et al 1408.4160)
- In order to satisfy this constraint, the source of the excess should be active only at redshifts $z \gtrsim 5$ (G.P. Holder 1207.0856)
- Even explanations in terms of new physics encounter similar difficulty: e.g., excess radiation from dark matter decays and/or annihilations would also produce anisotropies that have not been observed.
- "The radio synchrotron level reported by ARCADE 2 is spatially uniform enough to be considered a BACKGROUND. Thus, it would join the astrophysical backgrounds known in all other regions of the EM spectrum. ...**the origin of the radio background would be one of the mysteries of contemporary astrophysics**". (Singal et al., *The second radio synchrotron background workshop*, 2211.16547)
- "Highly accurate measurements.....The nature of the background is still unknown" (R. Sunayev 2408.01858)

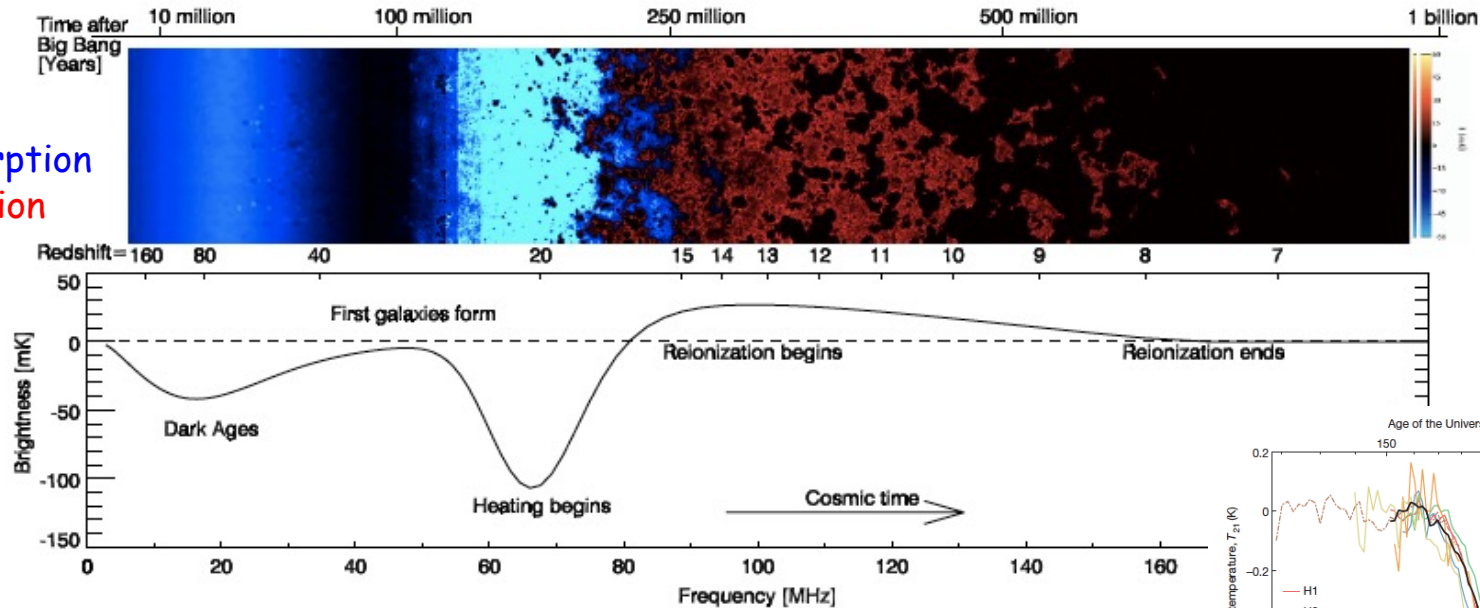
21cm cosmology:
shedding light on dark ages

21 cm cosmology (global signal)

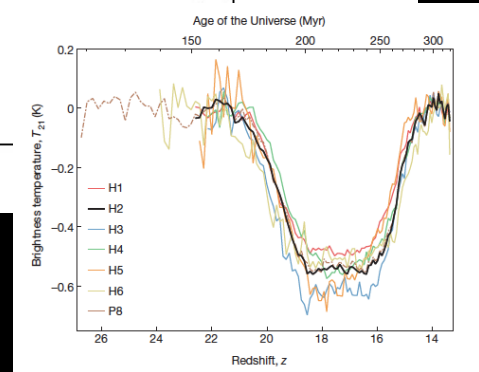
- 21 cm line (emission or absorption) is produced by hyperfine transitions between the two energy levels of 1s ground state of Hydrogen atoms. The energy splitting between the two level is $E_{21}=5.87\mu\text{eV}$
- The **21cm brightness temperature** parametrises the brightness contrast :

$$T_{21}(z) \simeq 23 \text{ mK} (1 + \delta_B) x_{H_I}(z) \left(\frac{\Omega_B h^2}{0.02} \right) \left[\left(\frac{0.15}{\Omega_m h^2} \right) \left(\frac{1+z}{10} \right) \right]^{1/2} \left[1 - \frac{T_\gamma(z)}{T_S(z)} \right]$$

spin
temperature



EDGES (anomalous) signal →



Upper bound on neutrino masses from the limit on DM contribution to Ω_0

At present:

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93.14 h^2 \text{ eV}} ,$$

$$\Omega_{\nu 0} h^2 \leq \Omega_{M 0} h^2 \lesssim 0.14$$

$\Rightarrow$

$$\sum_i m_i \leq 13 \text{ eV}$$

However a much more restrictive upper bound can be derived considering that neutrinos behave like HOT Dark Matter while we want it to be COLD !!!

$$\Omega_{\nu 0} h^2 \leq f_\nu \Omega_{M 0} h^2 \lesssim 0.14 f_\nu$$

$\Rightarrow$

$$\sum_i m_i \leq 13 \text{ eV } f_\nu$$

As we will see the fraction of hot dark matter is severely constrained from CMB+BAO data: $f_\nu < 0.01$!